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Flight Dynamics Analysis Branch End of Fiscal Year 1999 Report

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National Aeronautics and
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The contents of this report are based on inputs generously supplied by members of the Flight Dynamics Analysis Branch (FDAB), a subdivision of the Guidance, Navigation and Control Center (GNCC), at NASA/Goddard Space Flight Center (GSFC).

Additional information concerning FDAB activities may be obtained through the following Branch management:
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Published copies of this report will be available from Catherine A. Waltersdorff, Flight Dynamics Analysis Branch, Code 572, NASA/Goddard Space Flight Center, Greenbelt, MD 20771, as well as the NASA Center for AeroSpace Information and National Technical Information Service, both listed below.

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ABSTRACT

This report summarizes the major activities and accomplishments carried out by the Flight Dynamics Analysis Branch (FDAB), Code 572, in support of flight projects and technology development initiatives in Fiscal Year (FY) 1999. The report is intended to serve as a summary of the type of support carried out by the FDAB, as well as a concise reference of key analysis results and mission experience derived from the various mission support roles. The primary focus of the FDAB is to provide expertise in the discipline of flight dynamics, which involves spacecraft trajectory (orbit) and attitude analysis, as well as orbit and attitude determination and control. The FDAB currently provides support for missions involving NASA, government, university, and commercial space missions, at various stages in the mission life cycle.

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1.0 Introduction

This document summarizes the major activities and accomplishments carried out by the Goddard Space Flight Center (GSFC)'s Flight Dynamics Analysis Branch (FDAB), Code 572, in support of flight projects and technology development initiatives in Fiscal Year (FY) 1999. The document is intended to serve as both an introduction to the type of support carried out by the FDAB, as well as a concise reference summarizing key analysis results and mission experience derived from the various mission support roles assumed over the past year.

The major accomplishments in the FDAB in FY99 were:

- Provided flight dynamics support to the Lunar Prospector, MAP, and Triana missions, among a variety of spacecraft missions
- Sponsored the Flight Mechanics Symposium
- Supported the Consultative Committee for Space Data Systems (CCSDS) workshops
- Performed numerous analyses and studies for future missions
- Started the Flight Dynamics Laboratory for in-house mission analysis and support
- Complied with all requirements in support of GSFC ISO9000 certification
- Conducted acceptance testing of MAP ACS and C&DH flight software as part of the flight software testing team
- Provided launch support and anomaly resolution support for Landsat-7, TRMM, and ERBS.

2.0 Flight Project Support

2.1 Development Missions

2.1.1 EO-1 Earth Observing-1

Earth Observing–1, the first spacecraft in the New Millennium Program, is scheduled for launch in mid-April, 2000. The Guidance, Navigation and Control Center (GNCC) has multiple interests in the successful launch and operations of EO-1. Initially, EO-1 was solely a satellite to showcase more than 10 new and largely separate technologies. The foremost new technology was the Advanced Land Imager (ALI), which was intended as the next generation Landsat-type imager. The primary mission was designed to fly EO-1 one minute along track behind Landsat-7 and take the same image that Landsat-7 had just taken for comparison. The ALI detectors are located such that they cover the easternmost 1/5 of the Landsat-7 swath. There is also a cross track requirement of +/- 3 km which keeps the ALI detectors in the desired portion of the Landsat-7 swath. A second instrument, the GSFC Atmospheric Corrector (AC), was designed to operate with the ALI. About 1 year before launch, a companion instrument to the ALI and the AC, TRW's Hyperion instrument, was added to the spacecraft. This additional imager was to have flown on the failed Lewis spacecraft and will image a narrow swath that includes the westernmost 1/5 of the ALI swath.

Another GNCC-based technology is the Pulsed Plasma Thruster designed for attitude pitch control. Currently, the validation of this technology will occur after the prime imaging mission is completed.

The GNCC has played a major role in designing and implementing the EO-1 Flight Dynamics Support System (FDSS) which will provide flight dynamics support entirely within the EO-1 Mission Operations Center (MOC). After the first 60 days, Flight Operations Team (FOT) personnel will perform the entire flight dynamics function within the MOC. During the first 60 days, GNCC personnel will support the ascent and checkout phases of the mission. GNCC personnel must design the FDSS operational procedures and train the FOT to achieve operational expertise with the FDSS. There are four major areas of flight dynamics support for EO-1. They are: attitude validation and calibration, orbit determination, orbit maneuver control and orbit and attitude products generation. Most of these functions are supported with COTS-based software that has been adapted to meet EO-1 FDSS requirements. Approximately 60 percent of the FDSS EO-1 procedures will be executed via automation. This will reduce the execution time of certain FDSS tasks by a factor of 10.

The orbit maneuver control function showcases a major GNCC accomplishment. One of the EO-1 technologies is Enhanced Formation Flying (EFF), which has the goal of autonomous onboard orbit maneuver control. The FDSS will provide a ground-based EFF tool, AUTOCON-G, to validate the onboard EFF algorithms. After the first few months of ground-based EFF operations, designed to keep EO-1 in the strict formation with Landsat-7, the onboard EFF software, AUTOCON-F, will be designated as prime with the ground as a backup. The orbit and attitude product generation capabilities in the FDSS provide about three dozen products that aid in spacecraft health and safety maintenance, command generation in the MOC and image planning for the groups that built the ALI, AC and Hyperion instruments.

The FDSS has had all planned software releases delivered as of 7/31/99 and FDSS mission procedures are being written with 10/1/99 targeted as the completion date. The last 4 months before launch will include extensive simulations of the entire EO-1 ground system including the FDSS. To date, spacecraft integration and testing problems have delayed most ground system proficiency testing and simulations. The last quarter before launch will be one of the busiest in recent memory.

Finally, the GNCC has provided extensive mission analysis support to the EO-1 Project in the areas of trajectory and launch window computations for launch vehicle support, ascent maneuver planning to aid in Launch & Early Orbit timeline planning and product generation to support spacecraft and ground system Integration & Test activities.

[Technical contacts: Robert L. DeFazio/572; Richard J. Luquette/572]

2.1.2 EOS AM-1 Earth Observing System Terra

The EOS Terra spacecraft, formerly known as EOS AM-1, is currently in the final stages of preparation for launch from Vandenburg Air Force Base. Launch delays due to spacecraft hardware and mission operation center software modifications, as well as a recent investigation of the Atlas IIAS upper-stage rocket, has postponed the scheduled launch to the first quarter of FY 2000. Guidance, Navigation and Control (GN&C) activities during the prelaunch phase included a successful completion of the comprehensive performance test (CPT), a delivery of injection targets to the Lockheed Martin/Atlas team, as well as participation in various launch and early orbit and routine operations simulations.

GN&C testing in August 1998 resulted in the discovery of a voltage leakage condition in the Attitude Control Electronics (ACE) hardware. Specifically, it was found that an input signal that was outside the voltage range of the ACE Safe Hold Digital Processor analog MUX resulted in leakage into the other MUX channels. Input to the MUX consists of position, rate and magnetometer signals. The redundant ACE hardware was removed from the spacecraft to install zener diodes in order to limit the MUX input signals. The ACE was successfully reintegrated onto the spacecraft in January 1999.

In addition, the Flight Dynamics System was tested and enhanced throughout the year to meet changing mission requirements. An automation system, autoProducts, was implemented as a front end to the FDS. autoProducts allows a nonexpert user to access all of the Commercial-Off-the-Shelf (COTS) and Government-off-the-Shelf (GOTS) software that comprises the FDS through a common user interface, changing only those parameters necessary to generate planning products. The system significantly simplifies the process of generating the 85 required products from several different pieces of software, as well as minimizing chances for user errors.

[Technical contact: Lauri Newman/572]

2.1.3 EOS PM-1 Earth Observing System PM-1

EOS PM-1 Mission—Completed Flight Dynamics System (FDS) support requirements definition through meetings with the Project representatives, FOT members, and the Principal Investigators (PI's) for each instrument. Provided FDS inputs to the Mission Support Requirements Document (MSRD) based on the meetings and drafted Interface Control Documents (ICD's) for each entity. Performed orbit determination error analysis, contact requirements analysis, launch window/maneuver analysis, and provided preliminary inputs for attitude sensor calibration plan. Negotiated attitude sensor telemetry requirements with the spacecraft vendor. Supported project-level meetings with the spacecraft vendor, PI's, and other GSFC mission interfaces.

Several of the FDS Support Products for EOS PM had accuracy requirements of 1 second after 7 days. This requirement could not be met to 3-sigma certainty until approximately 1/2002 (using Schatten +2 sigma predicted solar flux values).

The accuracy of the FDS support products is limited by the accuracy of the predicted ephemeris used in the product generation. Knowledge of atmospheric density is necessary for the production of the predicted ephemeris, but the uncertainty in the atmospheric density model is proportional to the uncertainty in the solar flux. Daily solar flux variations are larger during high flux periods than when average solar flux values are low. Periods of high average solar flux (which peak near the planned PM launch date) result in greater uncertainty in the atmospheric model and consequently reduce the potential accuracy of the predicted ephemeris.

Flight dynamics (FD) orbit error analysis has shown that the 3-sigma, along-track uncertainty near the planned PM launch date is approximately 31 km at 7 days @ flux = 200 solar flux units (sfu), the +2 sigma flux prediction for this date. An along-track uncertainty of 31 km corresponds to ~4 seconds of uncertainty in the FD products. The FD products uncertainty is ~1 second @ 4 days when sfu = 200. The along-track and timing uncertainties at two other +2 sigma flux values (150 and 100) were also analyzed (see table 2.1 below) and the corresponding mean flux values at these times are included.

Table 2.1

Date	Solar Flux Mean Value (sfu)	Solar Flux +2 sigma (sfu)	Along-Track Error 7-day, +2 sigma Km (sec)	Along-Track Error 4-day, +2 sigma Km (sec)
12/2000	177	201	30.4 (4)	7.5 (1)
11/2001	139	150	9.3 (1.3)	
5/2003	97	100	1.4 (0.2)	

FDS had also received a requirement to provide a definitive ephemeris accurate to 15 meters root-sum-square (rss) for science data processing. FD personnel used the Orbit Determination Error Analysis System (ODEAS) to analyze this requirement using a variety of contact scenarios specified by the Project. Although the requirement theoretically was met according to ODEAS, the result (~14.7 meters rss) was too close to the requirement to guarantee 3 sigma accuracy since all sources of error are not modeled in ODEAS. The FD personnel negotiated with the project to relax this requirement to 20 meters rss based on these results.

Maximum 3-sigma Total Definitive Position and Velocity Errors Using Tracking Data From Wallops and Svalbard With Varying Definitive Lengths and Minimum Ground Elevation Angle Cutoffs. (See table 2.2 below.)

Table 2.2

	Total Definitive Position and Velocity Orbit Errors (3-sigma)					
	5-Degree Minimum Elevation Angle Cutoff		7-Degree Minimum Elevation Angle Cutoff		15-Degree Minimum Elevation Angle Cutoff	
Definitive Span (days)	Position (m)	Velocity (m/s)	Position (m)	Velocity (m/s)	Position (m)	Velocity (m/s)
1	30.96	0.0275	27.65	0.0257	26.53	0.0242
2	18.62	0.0155	17.00	0.0144	14.65	0.0127
3	21.40	0.0183	19.80	0.0170	17.44	0.0164

[Technical contact: David Tracewell/572]

2.1.4 GOES-L Geostationary Operational Environmental Satellite

The GOES-L spacecraft is the fourth of a five spacecraft series built by Space Systems/Loral and placed on station by a GSFC FOT supported by GNCC and Computer Sciences Corporation Flight Dynamics personnel. The first three spacecraft in the series were launched on an Atlas I launch vehicle (L/V). After that L/V series was phased out, the remaining spacecraft were manifested on an Atlas IIA. This later L/V had significantly more performance than the Atlas I, which allowed a transfer orbit redesign leading to more mission lifetime. That was the good news. On the reverse side, getting a firm manifest slot on the Atlas IIA has been a disaster. Our Flight Dynamics team planned no less than 7 mission profiles for GOES-L ranging from January 1999 to June 1999. Finally, we had a firm launch slot on May 15, 1999, had our Flight Dynamics team well trained and got to within 1 month of launch. Then, the Atlas IIA, along with several other launch vehicles, experienced a very serious RL-10 engine problem on its Centaur stage. The launch of GOES-L was postponed indefinitely while the FOT and the Flight Dynamics team try to remain intact and ready to support. The GOES Project attempts to sustain operational readiness by holding monthly simulations and proficiency testing until a firm launch date is selected. The best estimate for a launch of GOES-L, as of mid-August 1999, is sometime in the first quarter of calendar year 2000.

[Technical contact: Robert L. DeFazio/572]

2.1.5 InFocus Mission

Ultra Long Duration Balloon (ULDB) program

The InFocus telescope is an 8-meter-long astronomical x-ray telescope being developed at GSFC for flight on a high-altitude (40 km) stratospheric balloon. Whereas most pointed instruments on balloons use an azimuth/elevation system, InFocus is aiming to achieve arc second-level pointing performance using a single cup/ball oil-filled bearing between the pointed and nonpointed sections of the gondola. With this rotational isolation the pointed section, consisting of the telescope and support subsystems, is controlled similarly to an orbiting pointed payload, using reaction wheels, magnetic torquers, star trackers and gyros.

Studies are underway to specify critical control elements in the pointing control system via simulation and analysis. The complicated pendulous dynamics of the load train (connecting the balloon and gondola) due to aerodynamic loads are being studied to insure that disturbances on the pointed section due to mass unbalances about the ball center can be adequately controlled.

To this end, a demonstration balloon flight within the next year to measure disturbances is planned. No telescope will be on this flight. A second flight will carry the InFocus telescope using the standard azimuth/elevation pointing system. The third and final flight for InFocus will incorporate the ball/cup design and is anticipated to occur in 2 years.

Additionally, work is now underway to model and recommend changes to the standard 255-foot-long balloon train (consisting of all elements between the balloon and gondola, such as the parachute and separation systems) for the purpose of minimizing disturbance oscillations. This activity is intended to improve the performance for all pointed balloon payloads, particularly those that use azimuth/elevations designs. Depending on study results there could be a fourth flight within the next 2 years to qualify a newer train design.

The analysis required for all flights is being provided by the FDAB.

[Technical contact: David Olney/572]

2.1.6 Landsat-7

Landsat-7 Mission Support From GNCC

The Landsat-7 spacecraft was launched on a Delta 7920 expendable launch vehicle (ELV) from the Western Range (WR) at VAFB at 18:32:00.288 GMT on April 15, 1999. Post-deployment tracking, commanding and telemetry were provided by the Tracking and Data Relay Satellite (TDRS) and the ground sites located at Svalbard, Norway, Fairbanks, Alaska, Wallops Island, Virginia, and Sioux Falls, South Dakota.

Several orbit-raising maneuvers were performed during the first 90 days of the mission to take the Landsat-7 satellite from the Delta parking orbit to its mission orbit. As part of the orbit-raising sequence, the Landsat-7 satellite did a cross-calibration with the Landsat-5 satellite. During this cross-calibration period the Landsat-7 ground track was on the same World Reference System (WRS) as the Landsat-5 groundtrack. The cross-calibration period lasted approximately 2 days after which the Landsat-7 completed its ascent to mission orbit. The mission orbit for Landsat-7 is a 705 km, Sun-synchronous, near-polar orbit with a Mean Solar Local Time (MSLT) at the descending node of 10:00AM +/- 15 minutes. The orbit ground track repeats every 16 days. Periodic orbit adjust maneuvers are done throughout the life of the mission to keep Landsat-7 within 5 km of the WRS. Additionally, at least one inclination maneuver will be required during the life of the mission to keep the MSLT at the descending node within the mission limits.

Landsat-7 flight dynamics support was performed from the Landsat-7 MOC on designated flight dynamics workstations. The Landsat-7 orbit determination, acquisition data generation, product generation, maneuver planning and calibration, and attitude support were supported from the MOC. The attitude telemetry was received directly from MOC system and used for various attitude displays. Tracking data were received from the Space Network (SN) and several ground stations and used in the orbit determination process. Attitude telemetry was received and displayed at the flight dynamics workstations and processed for gyro bias determination. Flight dynamics also processed the Celestial Sensor Assembly (CSA) to assist in the verification of the onboard attitude determination system. Acquisition data and product generation are performed routinely throughout the mission.

The software system used for support of Landsat-7 GNC support was based on COTS software.

At launch +90 days, the Landsat-7 flight dynamics support was assumed by the FOT and will continue to be supported by the FOT throughout the life of the mission. All orbit determination, attitude support, acquisition data generation, product generation, and maneuver planning and calibration is done by the FOT. Flight dynamics personnel from the GNCC at GSFC will be available to the FOT for consultation during the lifetime of the mission.

In addition to flight dynamics support, the FDAB and GNCC provided real-time ACS flight support for Landsat-7 from launch simulations through launch, orbit maneuvers, and final instrument checkout. The ACS support provided by civil servant and contractor personnel helped to make the launch and early operations phase of the Landsat-7 mission go extremely smoothly.

[Technical contact: Sue Hoge/572]

2.1.7 MAP Microwave Anisotropy Probe

FY 1999 was a busy one for the MAP team as they ready for a launch in the second half of the year 2000. FDAB members of the ACS, flight dynamics, flight software, and flight software test teams began and completed a number of important milestones during the year.

A few remaining analysis issues were studied for the MAP mission during the year. These included further study of solar radiation pressure at L2 and its effect on spacecraft system momentum buildup. Additionally, a decision was made to mount a second Digital Sun Sensor (DSS) head to the spacecraft to provide further spacecraft rate backup during perigee passes, since it is possible that the radiation environment at that orbit altitude may cause the star trackers to be unreliable. Analysis of the orientation for the second DSS head was done to make sure that it would provide backup rates over an acceptable range of orientation during the perigee pass. A final ACS analysis activity that occurred during the fiscal year was support for the spacecraft Delta critical design review (CDR).

The major activity for FDAB personnel on the MAP team was support for flight software and flight software testing. Flight software walk-throughs of both hand-coded and "AutoCoded" (automatically generated flight software from the analysis and simulation tool XMath) software were supported. Additionally, spacecraft ACS FDC was further developed and began to be implemented and tested within the flight software. A number of critical flight software testing milestones were passed, as well. ACS flight software build testing was completed near the beginning of the fiscal year. At the time of this writing, acceptance testing of ACS and C&DH (Command & Data Handling) flight software is slated to be completed by the end of September 1999. An important goal of MAP's acceptance testing effort—the inclusion of flight dynamics and ground ops personnel early in the process, in order to clarify as many of the necessary interfaces as possible—was achieved.

The final MAP activity supported by FDAB personnel was spacecraft I&T. The TARA's, RWA's, and DSS's have been integrated to the spacecraft for initial checkouts. The MAC (main spacecraft electronics and processor) box has also been integrated. Various functional tests have been conducted on integrated hardware, including sensor and actuator phasing in all control modes. Additionally, the electronics interface to the propulsion subsystem has been tested. As this report is being written, I&T activities continue, and the FDAB members of the MAP team are gearing up to provide support for spacecraft CPT's.

The public MAP home page is at http://map.gsfc.nasa.gov. You can see real-time pictures of the spacecraft, the instrument, or the software test area at http://mapweb.gsfc.nasa.gov/wbforms/webpics/.

[Technical contacts: Steve Andrews/572; Karen Richon/572]

2.1.8 SPARTAN

Spartan 201-5

The Spartan 201-5 solar physics mission was launched on STS-95 October 29, 1998. It was deployed October 31 and successfully completed its 9-day mission for the Solar Astronomical Observatory (SAO) before being retrieved and returned to Earth. The FDAB supported the mission by determining the desired deploy orientation and computing the remote adjust values to be entered by the shuttle crew immediately before deploy.

Spartan 250

The Spartan 250 series of spacecraft is planned to be an upgrade of the existing Spartan 200 series. It is designed for better performance and increased mission lifetime. It will have a Power PC CPU-based digital attitude determination and control system and an RF communication capability.

The Spartan 251 missions will carry an experimental microsatellite mission for the Air Force. Preparations for the Spartan 251/XSS-10 mission were stopped in May when it was determined that the mission would not be manifested within a timeframe acceptable to the Air Force. The XSS-10 mission will now be flown on an ELV, without the Spartan carrier. Before work was halted the digital ACS, onboard environmental models, and dynamic simulator algorithms had been fully developed and tested, and were being transferred to flight software.

We are now working on the Spartan 251/XSS-11 mission that is scheduled for launch in the 2002–2003 timeframe. Only slight modifications to the existing Spartan 251/XSS-10 ACS algorithms described above will be required to support this mission. The design lifetime for this mission will be greater than that of the XSS-10 mission. This will result in a need for reaction wheel actuators and further modifications to the ACS algorithms.

Spartan Lite

The Spartan Project has discontinued proposal work on the Spartan Lite spacecraft. It was determined that the need for small spacecraft buses of this sort is being adequately met by industry so the focus is now on Spartan 250 and Spartan 400 spacecraft.

Spartan 400

Spartan 400 is Spartan project's newest proposal. This carrier will extend the mission life from 12 days of Spartan 200 series to 12 months. It is shuttle-launched and will be able to house large instruments (1 meter plus and 2000 pounds). Since the carrier and the instrument are retrievable, it provides the space industry the ability to obtain science quickly, inexpensively and at a lower risk.

Spartan 401 is an Earth pointer with half a dozen instruments on board, including LIDAR, STW/AR, SHIMMER, GPSOS, OOAM, StOLSS. LIDAR is nadir pointing; STW/AR includes six antennas pointed towards nadir; SHIMMER points towards limb and includes limited lunar track; GPSOS includes three large antennas with specific orientations; OOAM is a limb pointer that tracks sunrise and sunset with movable optics; StOLSS is a limb pointer that requires unobstructed FOV. The required orbit is 450 km x 450 km; the desired orbit is 600 km x 600 km. Inclination is 51.6 degrees. The attitude and pointing control accuracy and knowledge varies. The first task for the ACS analysis team was to develop an error budget bounding the performance capability based on the selected sensors and actuators for Spartan 400 series. The analytic results were verified with simulations. Based on the analysis results we provided, ACS imposed requirements on the other subsystem, such as optical bench thermal warping, solar array thermal snap, etc. Ground tracking over +/-30 degrees was also studied. The ACS analysis team was also heavily involved in the solar array design to ensure its orientation is attitude-control favorable, by investigating the aerodynamic torque and its effect on wheels and torquers sizing for each configuration. In addition to the analysis, ACS analysts also participated in the development of the product development plan in the area of coordination systems definition, control modes and performance specification, ACS-derived requirement definitions and hardware specifications.

Spartan 402 is an advanced solar coronal mission with two coaligned instruments: spectroscopic and polarimetric coronagraph (SPC) mounted to a central mounting plate (CMP). A 10-meter-long deployable mast also mounts to the CMP, positioning an external occulter assembly 10 meters forward of the SPC aperture. Spartan 402 will be deployed at a 300 km attitude with 28-57 degree inclination and raised to 580 km. Because the 10-meter-long boon has a significant mass at the tip, the ACS analysis team performed stability analysis and the tip mass deflection effect on the spacecraft attitude performance. ACS analysts also assisted the structure and instrument team in defining the design requirement of the boon in terms of structure frequency, damping ratio and modal gain. In addition to the conventional attitude sensors for the Spartan 400 series, the fine attitude is from the instrument Guide Telescope (GT) with fine steering mechanism that has an 8.5 x 8.5 arc-minute field-of-view. Since this GT is flown on TRACE, the GT FOV searching algorithm can be adopted. However, detailed error budget was needed for the fine Sun acquisition to ensure the GNCC's capability to locate the Sun within the FOV of the TRACE guide telescope/ISS. The analytical error budget result was crossed checked with a simulation. Additionally, analysts participated in the development of the Product Development Plan in the area of coordination systems definition, control modes and performance specifications, ACS-derived requirement definitions and hardware specifications. A Spartan 402 proposal was submitted in July and an oral review was held on August 19.

[Technical contacts: Josephine San/572; Jim Morrissey/572]

2.1.9 Triana

The past year has been an incredible challenge for the Triana ACS analysis team. This is a project with a very tight schedule. The baseline design, SMEX-lite, a protoflight spacecraft designed in-house, was conceived for low-Earth orbiting spacecraft. The ACS system required extensive modifications to accommodate a mission to the L1 libration point. Working in a concurrent engineering environment, the team is continually challenged to respond to constantly changing requirements. To mitigate the requirements creep, the team created a flexible design capable of accommodating the observatory's evolving requirements. We have successfully completed control system analysis for the Triana ACS, to the satisfaction of the Triana project.

All of the onboard controllers have been designed and simulated, proving our performance meets our requirements. Work is currently underway to support software implementation of our controller design. At the same time, the team is preparing to support in-house integration and testing of the Triana spacecraft, beginning in the fall of 1999.

Triana is the latest mission planned to visit the Earth-Sun libration point. From L1, Triana will have a full-disk, sunlit view of the Earth at all times. Triana will provide pictures of the full sunlit Earth on the Internet every 15 minutes. FDAB took Triana from a mission concept to a mature mission design in just a few months. FDAB worked with Triana PI's to alter the baseline mission trajectory to better meet science objectives. The current mission includes a Lissajous orbit about L1, a shorter transfer time to L1 and improved Sun-Earth-vehicle angles. The baseline trajectory is the first Lissajous orbit to be designed using Dynamical Systems Theory (DST) from Purdue University. DST is an analytic approximation of classes of orbits that intersect L1 and the Earth. DST greatly improves the efficiency of the mission design process and the fuel-efficiency of the trajectory design. FDAB worked closely with ACS and propulsion engineers to design an ACS and propulsion system that would meet mission requirements. This included number and placement of spacecraft thrusters, fuel tank sizing and attitude modes. FDAB worked closely with the Johnson Space Center on space shuttle launch and deployment scheduling. Triana requires four deployment opportunities for any launch time, with a crew sleep cycle in between, and within ground station coverage.

Figures 2-1/-2/-3 represent views of the Triana spacecraft and the orbital trajectory.

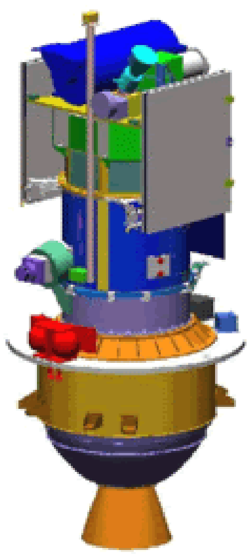
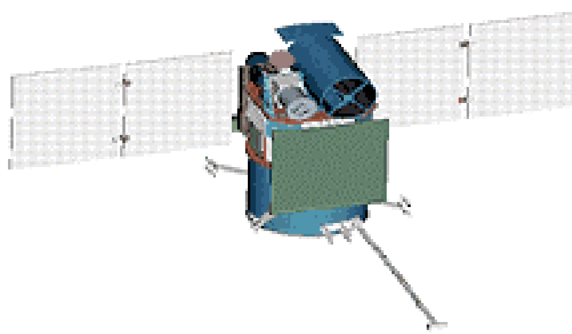


Figure 2-1



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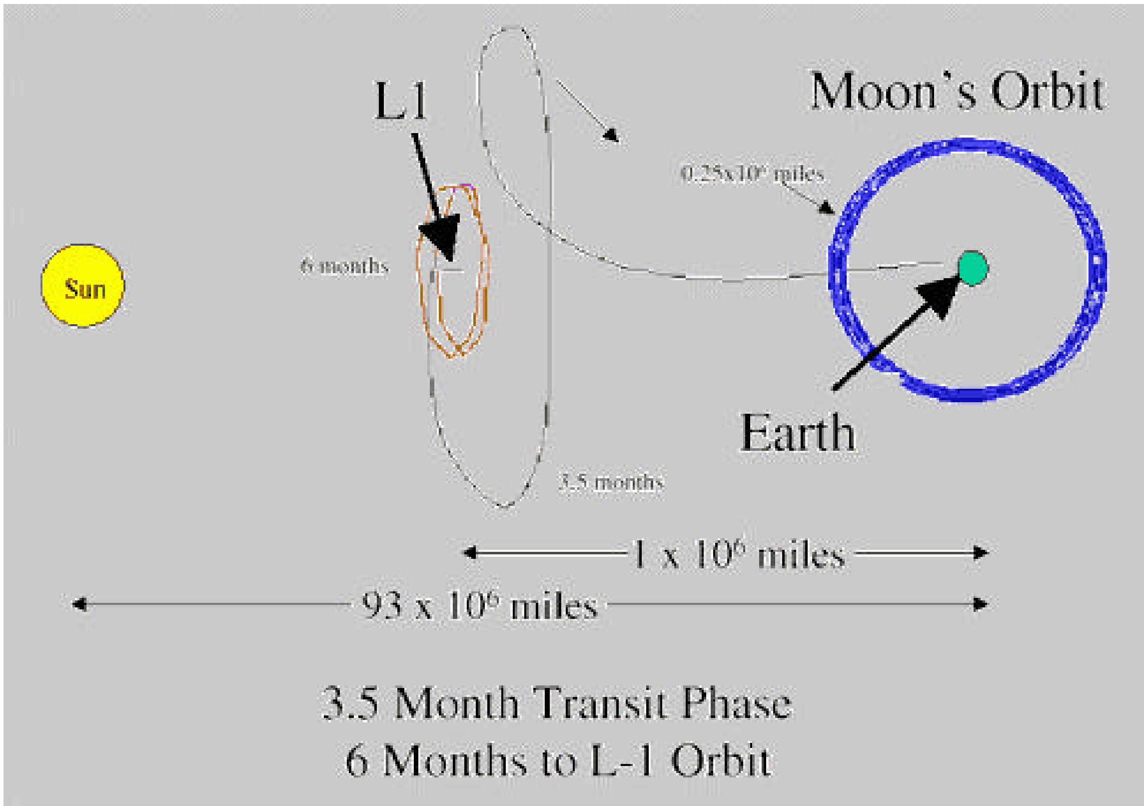

Figure 2-3

For complete details about the Triana mission refer to http://triana.gsfc.nasa.gov/home/

[Technical contacts: MarkBeckman/572;Greg Marr/572; Wendy Morgenstern/572]

2.1.10 WIRE Flight Dynamics Attitude Support

The FDAB successfully supported the Wide-Field Infrared Explorer (WIRE) launched on March 5, 1999. Shortly after launch, the spacecraft started spinning out of control due to the science instrument cover being blown early. The pyrotechnics controlling the hatch opening malfunctioned and the heat from the Sun in conjunction with onboard cryogen conspired to create an unanticipated thruster which was beyond the capabilities of the attitude actuators to control. FDAB personnel provided attitude determination and rate estimation support as well as providing various unplanned planning products until the spacecraft was successfully transitioned to pseudo-normal operations though with a severely damaged science instrument. Once in normal operations, FDAB personnel performed a calibration of the gyros. An example of the pre-calibration results can be seen in figure 2-4, and the resulting post-calibration results can be seen in figure 2-5.

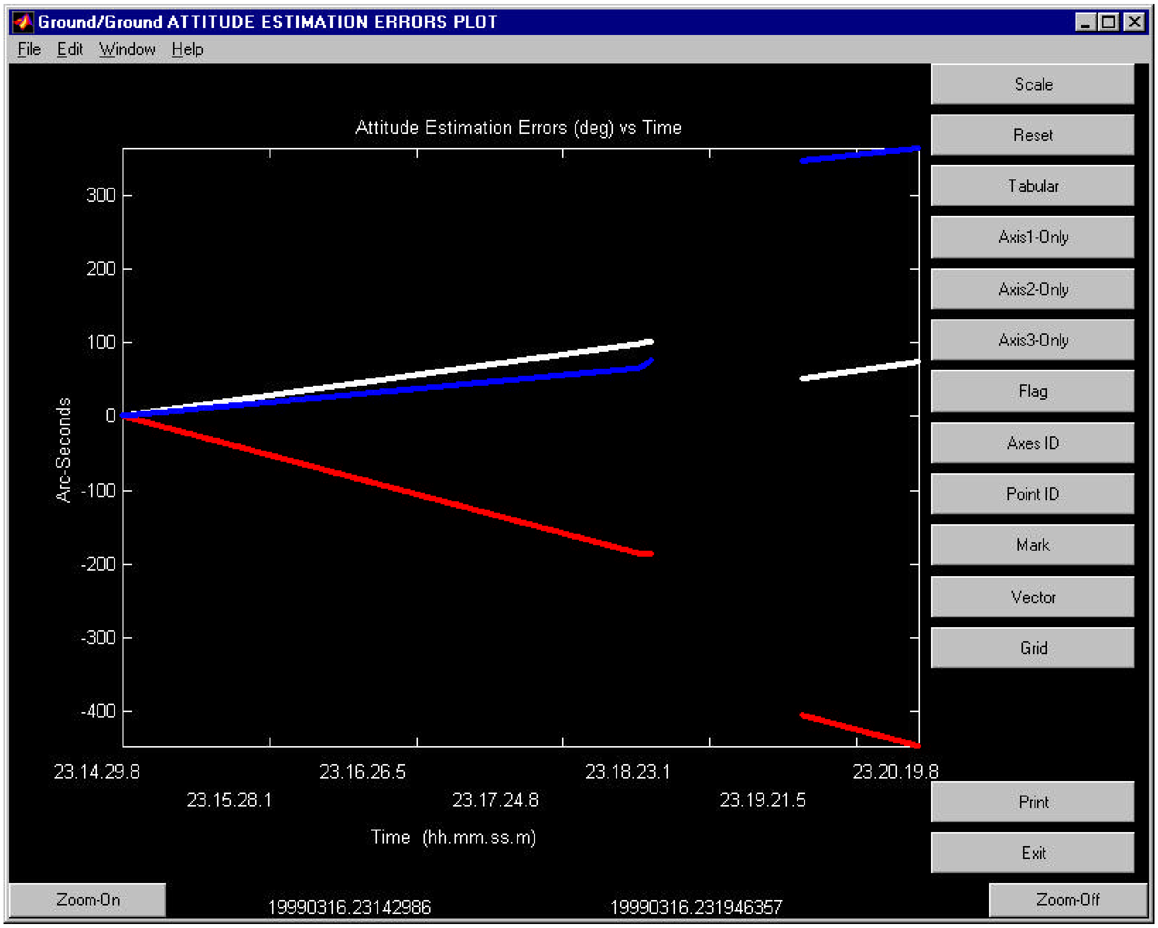

Figure 2-4 WIRE Gyro Pre-Calibration Result

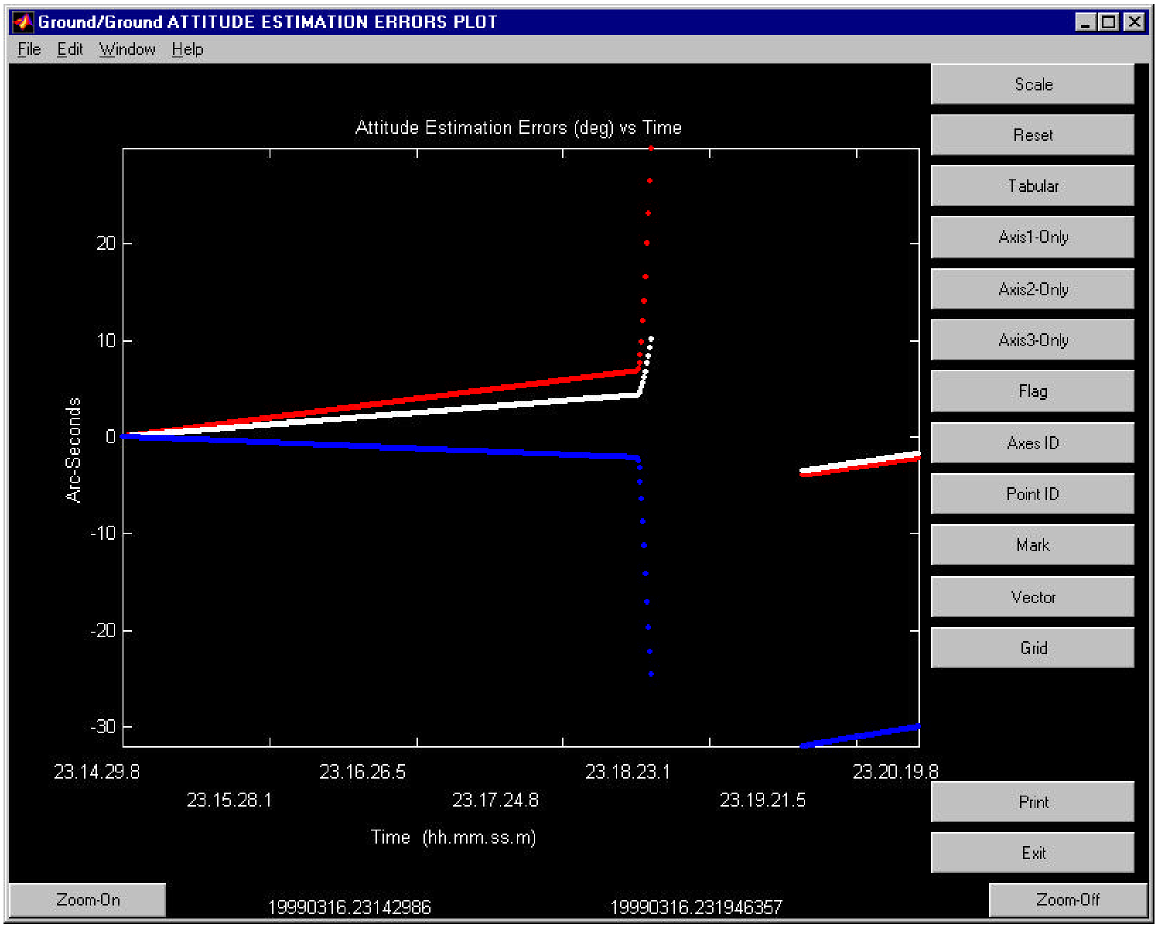

Figure 2-5 WIRE Gyro Post-Calibration Result

[Technical contact: Rick Harman/572]

2.2 Operational Missions

2.2.1 ERBS Earth Radiation Budget Satellite

The ERBS spacecraft, which was launched in 1984, experienced an under-voltage condition on battery #2 due to cell failures. This failure, which occurred on January 16, 1999, caused the ACS to autonomously enter the B-Dot mode. Note that this was the first time that ERBS ACS had ever autonomously entered B-Dot mode. Following the successful commanding of the spacecraft back to normal ACS pointing mode, a full-scale effort was made in order to recondition battery #1, which was disconnected in 1993 due its own cell failures. Resolution of this anomaly has returned ERBS to a safe power configuration, thereby enabling the ACS to provide the required attitude pointing as well as the periodic 180-degree yaw maneuvers. This has allowed for the resumption of science-gathering activities.

[Technical contact: Samuel J. Placanica/572]

2.2.2 Lunar Prospector

Lunar Prospector (LP) completed its primary mission on December 31, 1998. The LP Extended Mission was authorized for 6 months and included a lower altitude above the lunar surface. On January 19, 1999, GNCC planned the maneuvers to lower the altitude to a mean of 40 km. After 1 month, the altitude was again lowered to a mean of 30 km. GNCC planned all spacecraft maneuvers, including monthly maintenance maneuvers required to keep LP in its orbit. GNCC also performed all orbit determination including maintaining a web site with all LP definitive ephemerides (fdd.gsfc.nasa.gov/lp) for instant access by mission controllers or PI's. On July 30, 1999, the first of two final maneuvers was performed to raise apoapsis to target the final impact of LP into a permanently shadowed crater on the lunar southern pole. On July 31, 1999, LP's final maneuver was performed on the dark side of the Moon and LP was never heard from again. GNCC provided complete flight dynamics support to the operations center at Ames Research Center. As part of targeting the final impact, improved lunar topography was needed. GNCC worked with ARC, University of Texas, GSFC Code 900, and the Smithsonian to obtain the best estimates of lunar topography around the impact site. All indications are that the impact was on target. Analysis of the final impact and the determination of water content are still ongoing.

Figures 2-6/-7 represent the final trajectory.

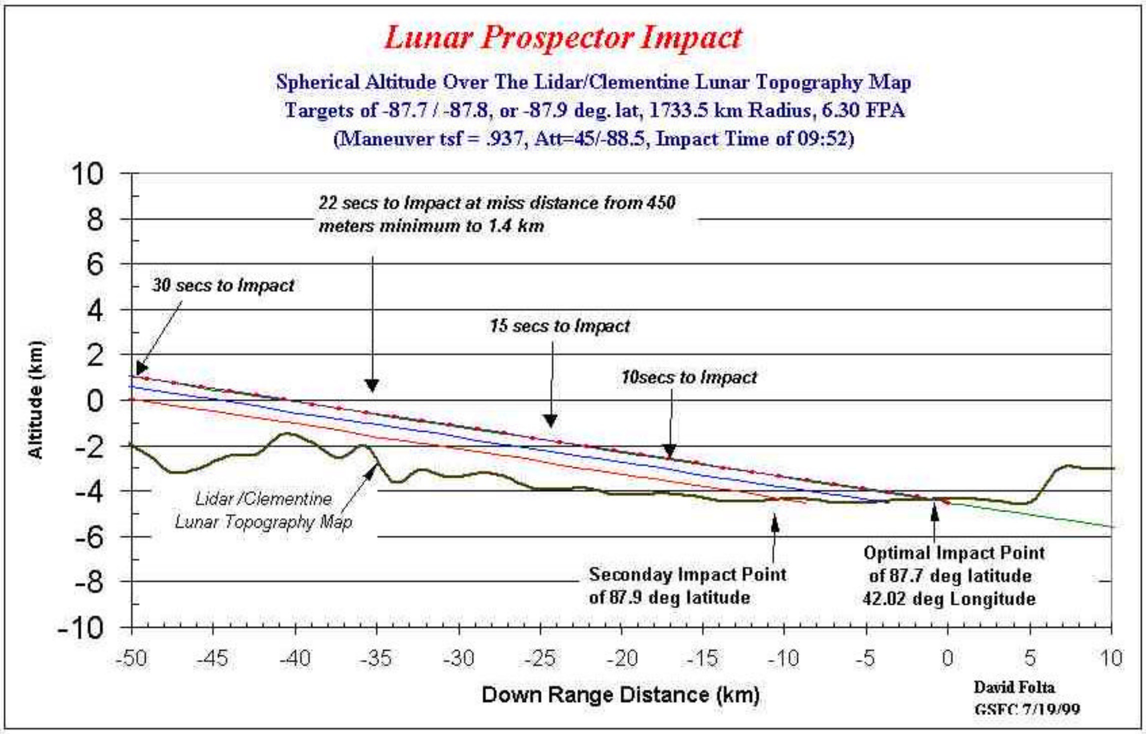

Figure 2-6

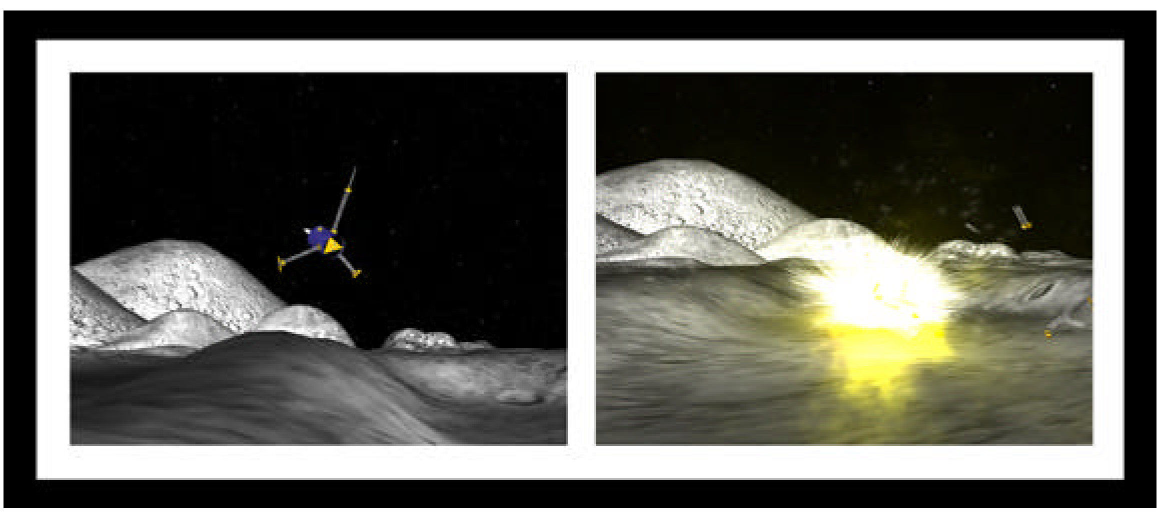

Figure 2-7

[Technical contacts: David Folta/571;Mark Beckman/572]

2.2.3 TRMM Tropical Rainfall Measuring Mission

The TRMM ACS has been successfully providing the required performance with respect to attitude pointing and maneuver capabilities throughout FY 1999. This includes the periodic 180-degree yaw maneuvers to maintain thermal constraints, as well as orbit-raising maneuvers using thrusters in order to keep the spacecraft at its 350-km orbit altitude.

During FY 1999 a number of spacecraft issues required attention. The first of these issues was that the drive for the minus Y solar array had been experiencing temperatures above the qualified test levels since early mission operations. These high temperatures could result in a failure of the array drive, thereby stopping the array. This situation would create a larger-than-designed-for aerodynamic torque environment which would result in higher momentum unloading requirements for the ACS. The failure would also effect the capability of the power subsystem. A long-term study was undertaken by various spacecraft subsystems, including ACS, to see what could be done. The first action of the study was to reduce the range of motion for the arrays in order to decrease the integrated angular motion for the minus Y array drive. The study then investigated the possibility of "parking" the minus Y array at an angle that would satisfy power requirements with the least amount of impact to the ACS with regards to attitude pointing and momentum unloading. Parking the minus Y array at an angle of 30 degrees was deemed acceptable by the investigation group; however, the group's recommended course of action was to not park the array. This recommendation was based upon the benefits as well as the risks to spacecraft operations of a parked array configuration. Results of the study were presented to a review panel at which the panel agreed with the investigation's findings and recommendations. Procedures and actions have been designed for future operations in case it is deemed necessary to park the array, or if the array drive does malfunction.

The second spacecraft issue for TRMM during FY 1999 was that a thermally induced flexible mode of the solar array boom was magnified to unexpected levels at high solar beta angles (54 to 58 deg). This resulted in a noisy gyro signal which is used to drive the magnetic torquer bars (MTB) for momentum unloading purposes. A software test within the ACS fault, detection and correction (FDC) logic switched from the nominal 50/50 usage of each of the two coils for each bar to 100% usage of the backup coil. Once it was realized that the MTB's were not at fault, the FDC test threshold was increased and nominal 50/50 commanding of the MTB was re-enabled. The noisy gyro is also used to compute solar array drive commands, resulting in noisy commands to the array drive. This "closed-loop" situation may be reduced under a proposed ACS code patch which is currently under investigation.

[Technical contact: Samuel J. Placanica/572]

3.0 Study Missions Support

In FY99, the GNCC continued its participation in supporting a wide variety of future mission concepts. This section describes the analyses performed which range from science instrument feasibility studies to full mission concept definitions.

3.1 IMDC Integrated Mission Design Center

The Integrated Mission Design Center (IMDC) is dedicated to innovation in space mission design & advanced concepts development to increase value for NASA and its customers. In the IMDC, subsystem engineers (e.g., mission design, attitude control, propulsion, mechanical, communications, thermal, command and data handling, power, and ground systems) gather to conceptualize and perform mission trade studies in the presence of the customer (i.e., Project Scientist, Principal Investigator, etc.). The end result is a spacecraft design and an operations concept that the customer can use in proposal development for new mission opportunities (i.e., Announcements of Opportunity).

The IMDC became operational in spring 1997 and as of this writing has supported over 50 mission studies and focus sessions for both Earth science and space science applications. A typical IMDC study session begins with a mission design briefing by the customer. The briefing is followed by design sessions to perform the system and subsystem level trades agreed upon with the customer. Typical design sessions last from 1–2 weeks. On many occasions, multiple visits to the IMDC are needed as a mission concept matures.

GNCC analysts support the IMDC using their expertise in trajectory design, orbit analysis, and mission planning as well as ACS design, ACS hardware selection and performance evaluation. A sample of the IMDC missions supported by the GNCC in FY99 included:

- ***Coriolis:*** Coriolis is a Naval Center for Space Technology (NCST) mission designed to measure surface level wind direction and speed over the ocean using a microwave polarimeter. The NCST used the IMDC on two occasions as a simulated Rapid Spacecraft Development Office (RSDO) vendor to evaluate their requirements specifications document. GNCC analysts analyzed the ACS requirements, orbit selection, and maneuver requirements, and assisted in the operations concept analysis.

- ***NPOESS Preparatory Project (NPP):*** NPP intends to demonstrate and validate pre-operational instruments and algorithms prior to first flight of NPOESS (NOAA Polar Orbiting Environmental Satellite System). NPP visited the IMDC twice in FY99. The first visit was to evaluate the requirements for creating a baseline design. The final visit was to evaluate the design against potential spacecraft found in the RSDO catalog.

- ***EO-3 Nexus/RedEye:*** The IMDC supported 3 weeks of analysis on the Nexus/RedEye collaboration for the EO-3 competition. GNCC analysts supported the operations design concept of moving Nexus/RedEye from a low-Earth, shuttle orbit to geostationary orbit. Trade studies were performed on different propulsion methods (solid/liquid, all liquid, solid/solid) and in the end, a dual-solid motor architecture was adopted. ACS work involved analyzing the two different observing modes of this proposal—Earth pointing for RedEye and stellar pointing for Nexus, and working with instrument control engineers and PI's to establish necessary ACS accuracy and jitter requirements. ACS analysts also devised necessary control modes for the different phases of the mission and recommended the necessary components for each mode. Trade studies were performed on one star tracker versus two; gyro selections to accommodate extreme high rate and low rate; four reaction wheels versus three; and Global Positioning System (GPS) options for future technology research.

- ***MAXIM:*** The Micro-Arc-second X-ray Imaging Mission (MAXIM) involves the formation flying of separate optics and detector spacecraft to collect x rays in a heliocentric drift-away orbit. The mission concept relies on an entirely new concept of formation flying. GNCC analysts worked to try to validate the MAXIM concept. In order to achieve their x-ray science, the MAXIM PI requires a 450 km focal length between his optics and detectors. It is desired to obtain this focal length by formation flying the optics and detectors as two independent spacecraft. The challenge is to formation fly the detectors around the optics at a specific range and maintain this range and attitude to point at celestial targets for observations on the order of 7 days. When a new target is selected, the optics will slew to the target but the detectors must correct its orbit to move in space relative to the optics and maintain the 450-km focal length. Work will continue outside of the IMDC to simulate the formation-flying concept. Another challenge of the MAXIM mission is the 0.5 milli-arc-seconds pointing accuracy requirement for the optics spacecraft and the 3-mm lateral pointing accuracy requirement for the detector spacecraft. ACS analysts worked with the PI to derive ACS pointing accuracy and jitter requirements, performed simulations to assess feasibility to adopt NGST design for coarse pointing, and analyzed fine pointing using the instrument sensor as an attitude sensor to close the loop. ACS modes for both the optics and detector spacecraft were derived and sensors for each mode were selected. Trades were performed on actuator selection (reactions wheels, pulsed plasma thrusters, or both) for rate null/Sun acquisition, science, and slew control.

- ***DS-5 Collaboration:*** GNCC analysts supported the IMDC effort to evaluate three potential DS-5 missions as part of NASA's New Millenium Program (NMP). Work included mission concept brainstorming of the three options—a solar sail demonstration, a force-free spacecraft pair for detecting gravity waves, and a nanosat concept to evaluate miniaturization of instrument and hardware technologies.

- ***MFV:*** The Maxwell, Faraday, Vlasov (MFV) is a 1-month mission designed to directly measure electric currents using the three independent techniques proposed by physicists' whose names comprise the project name. One of the three techniques involves the release of 12 miniature free-flying magnetometers (FFM's) prior to entry into high auroral activity at three times during the mission. The main spacecraft would receive data from the FFM's over one-half to three orbits. GNCC analysts worked with the PI to examine FFM release velocities and subsequent relative motion. Minimizing the relative range between the FFM's and the main spacecraft maximized the science return. Attitude control work involved defining spin axis orientation, spin rates, control modes and functions of each control mode. ACS analysts specified the locations and alignment requirements for magnetometers and magnetic coils. Sizing of spin and precession coils was based on the FAST mission. Since MFV is a slow spinner, managing the inertia ratio is critical. ACS analysts worked closely with the structure designer in the arrangement of the hardware. This mission was made more challenging by the requirement to fly as a secondary payload.

- ***Extremely Heavy Galactic Cosmic-Ray Composition Observer (ECCO) & Cosmic Ray Energetics and Mass (CREAM):*** In addition to Earth-orbiting free-flyers, IMDC work has included the support of two balloon payloads designed to measure cosmic rays. GNCC support has primarily been in the area of identifying ACS components to meet the instrument pointing requirements. Further analysis was performed to understand the implications of the balloon disturbance environment. Analysts also supported communications link studies.

[Technical contacts: Jennifer Bracken/571; Michael Mesarch/572; Dave Olney/572; Josephine San/572; Frank Vaughn/572]

3.2 Mission Concept Support

In addition to IMDC support, GNCC analysts supported other varied mission concept studies:

Sun-Earth Connections (SEC) Roadmap: GNC mission analysts supported mission design activities for the SEC Roadmap. In all, 12 mission concepts were examined for methods of collecting the desired science data. The 12 missions included conventional, low-Earth orbit, geosynchronous orbit, highly elliptical Earth orbit, non-Keplerian 'pole-sitters' above the Earth, and orbits at or inside Mercury's orbit (0.39 astronomical units). The science data capture was accomplished with single satellites or constellations of up to 40 satellites. In supporting the roadmap, it was apparent that many missions would benefit greatly from advances in solar sail technology and miniaturization of instruments and components.

Global Electrodynamics Connections (GEC): The GEC mission involves taking in situ measurements of the Earth's ionosphere using four identical spacecraft. The four spacecraft will fly in formation (as close as 8 km) to examine the variability in the ionosphere. As these spacecraft fly at such low altitudes, atmospheric drag will continually cause the orbit to decay. Mission analysts continue to examine the amount of propellant necessary to provide for ample science return during a 2-year mission. Further analysis on the launch initial conditions and evolution of the perigee latitude and local time history will help the GEC science team to plan for interesting and varied ionospheric conditions (e.g., combinations of season, day vs. night, auroral vs. mid-latitude, etc.). GEC has also visited the IMDC on three separate occasions for iterations on the spacecraft design. During these visits, ACS engineers have continued to refine hardware selection. Included in the analysis is the feasibility of designing an Integrated Power and ACS (IPACS) flywheel system—a new technology development.

Magnetospheric Multi-Scale (MMS): The MMS mission is designed to investigate the Earth's magnetosphere in the regions of the magnetopause and plasma sheet. Five spacecraft will fly in a loose formation that will form a double tetrahedron at orbit apogee. The mission consists of four phases in which the orbit ranges between 1.2 x 12 Earth radii (at 10-degree inclination) and 10 x 50 Earth radii (at 90-degree inclination). Flight dynamics analysis support for the past year has consisted primarily of conferring with the Project Manager and Project Scientist to formulate mission science requirements and spacecraft operational requirements and performing analysis to identify and resolve conflicts as related to the orbit design. Analysis to determine the effect of launch epoch and initial clock angle, with respect to the magnetosphere, on maximum shadow length and dwell time in the plasma sheet during Phases 1 and 2 is nearing completion. Analysis tasks for the upcoming year will include the design of the two sets of double lunar swingbys (Phase 3) required to transition to the Phase 4 orbit and development of an efficient control strategy to maintain the double tetrahedron at orbit apogee throughout the mission life.

Space Weather Concepts: GNCC analysts provided inputs to GSFC scientists for a Space Weather Workshop in April 1999. Analysts assisted in assessing feasibility of several different mission concepts. The missions included a solar-polar orbiter, simulated solar comet, and a distant retrograde orbit (DRO) constellation. Interest in a four spacecraft DRO, to monitor solar weather with 10 times the response time of SOHO, has prompted a future paper in The Journal of Atmospheric and Solar-Terrestrial Physics.

[Technical contacts: Greg Marr/572; Michael Mesarch/572; Karen Richon/572; Frank Vaughn/572]

4.0 Technology Development Activities

4.1 Advanced Mission Design (Dynamical Systems Theory)

Dynamical Systems Theory (DST) is being used by the GNCC to design trajectories for libration point orbits. DST techniques improve the mission design process by allowing one to first choose the desired mission orbit and then work backwards to find the transfer trajectory. Traditional mission design techniques, as applied to libration point orbits, often rely on inefficient "hit or miss" shooting techniques requiring numerous simulations.

The DST work has been performed in partnership with Purdue University. Purdue graduate students, in conjunction with their university advisor, Dr. K. C. Howell, have made significant contributions to the GNCC's mission design efforts. Their work on the Triana trajectory design is especially noteworthy; it would be extremely difficult, if not impossible, to evaluate the numerous candidate Triana trajectories, without the use of DST techniques.

Mark Beckman of the GNCC and Jose Guzman of Purdue University presented a paper on the Triana Mission Design, which included a discussion of the DST techniques involved, at the Alaska AAS conference.

[Technical contact: Steven Cooley/572]

4.2 Autonomous Relative Navigation & Formation Flying

In October 1998, NASA/GSFC initiated efforts to coordinate the formation-flying and virtual platform technology development programs. In parallel with these efforts, the Cross-Enterprise Technology Development Program (CETDP) was restructured to create 10 technology Thrust Areas (TA). As a result of these changes, the GSFC formation-flying program gained a larger role within the agency. GSFC was selected as the lead center for Distributed Spacecraft Control. Working in close cooperation with the CETDP Thrust Area Manager (TAM) for Distributed Spacecraft Control, Kate Hartman, GSFC expanded the formation-flying program and broadened its scope.

One of the major highlights of FY99 was the creation of a partnership between NASA and the Air Force Research Laboratory (AFRL). AFRL has instituted a program to push technology development to support their TechSat 21 mission. This program involves 10 universities developing and flying nanosatellites in various formations. AFRL asked the GSFC formation-flying team to help evaluate the university submissions they received for the nanosat program. In particular, AFRL wanted GSFC to take the lead role for formation-flying aspects of the program and to rank the proposals accordingly. The formation-flying team, with the help of CETDP Distributed Spacecraft Control Thrust Area, decided to take this a step further and augment the selected university funding to develop technologies of specific interest to NASA. In May, a Request For Information (RFI) was posted seeking proposals that would develop underlying technologies necessary for formation flying. As a result of the RFI, 10 interesting technologies were selected and paired with spacecraft to provide a flight opportunity. Currently, the universities are continuing with AFRL to plan the missions and design their spacecraft with NASA/GSFC/GNCC technologies incorporated.

The GSFC formation-flying team wrapped up the Earth Science Technology Office (ESTO)-funded studies in formation control. These studies included analysis by Johns Hopkins University/Applied Physics Laboratory (JHU/APL), AI Solutions, and Stanford University. The JHU/APL work looked at defining the general requirements of formation-flying missions. The AI Solutions work included incorporating formation-control techniques and modeling in FreeFlyer. The Stanford study examined using differential GPS to determine high-precision spacecraft relative positioning. ESTO was not able to fund subsequent work in this fiscal year. However, a follow-on effort was instituted thanks to funding from CETDP. This work at the Massachusetts Institute of Technology (MIT) includes analysis and algorithm development to specify the number of spacecraft needed for any particular interferometry missions.

In December 1998, the formation-flying team supported the first CETDP Distributed Spacecraft Control Workshop. The workshop was an invitation-only affair to exchange program information, progress and ideas. The workshop was a great success. It served as a kickoff for the CETDP and the materials from the workshop are still in high use today. It was the first opportunity to get most of the NASA-distributed spacecraft players together in one place to exchange ideas.

During FY99, the Formation-Flying Team completed the design, development and testing of the EO-1 Enhanced Formation Flying (EFF) flight code. With this code and the incorporation of the flight version of AutoCon, also completed during this fiscal year, the EO-1 spacecraft will be able to autonomously maintain formation with Landsat-7 using multiple algorithms for control. Currently, GSFC and the Jet Propulsion Laboratory have algorithms that will be used during the mission. However, the flight system has been designed such that other algorithms could be uploaded after launch to further test and enhance the formation control of EO-1.

As FY99 went on, the FDAB began developing the Formation Flying Testbed (FFTB). The FFTB is a joint project between GSFC, the Hammers Co., JHU/APL and AI Solutions. Funding for this effort includes SBIR's, CETDP and SOMO money. The testbed will include GNCC's GPS testbed to create an environment that allows algorithms, hardware and other technologies to be developed and tested for formation control. The testbed uses the Hammers Co.'s VirtualSAT Pro to provide a dynamic simulator for a spacecraft or series of spacecraft as well as a hardware interface for any test hardware. AI Solutions' FreeFlyer provides a graphical display for the testbed.

Also during FY99, the GSFC formation-flying team supported the Technology Development for Explorers Missions NASA Research Announcement (NRA). The team supplemented the NRA with additional funding targeted specifically for formation-flying efforts. The team also submitted some proposals to the NRA. A submission by Russell Carpenter for Decentralized Estimation and Control of Distributed Spacecraft was accepted and funded. This effort includes using the FFTB to test Dr. Carpenter's control algorithms and provides a small amount of additional funding for the FFTB. Also, a submission by JHU/APL to develop a crosslink-transceiver was selected. This transceiver will be flown on board some of the university nanosats. Also, a submission by Jim Garrison for development of a GPS receiver suitable for use by formations of satellites in highly elliptical and geosynchronous orbits was accepted and funded. This effort will make use of the FFTB to test GPS relative navigation algorithms.

The GSFC formation
from March through May. This effort included reviewing the entire set of EOS, EX and OP missions and suggesting technologies that could be used on certain missions and the benefits of those technologies. These technologies were included in the final submission to
EOS missions.

The formation Submillimeter Probe and the Evolution of Cosmic Structure (SPECS) mission development. Team member Dave Quinn provided the SPECS team with spacecraft design suggestions to meet their complicated mission requirements. Dave's design allowed the spacecraft to accommodate the complex dynamics of multiple collectors moving in tight and drifting further out. The SPECS mission continues to evolve and has very changing requirements.

The formation flying team continues to support the Earth Science Vision. Team members have participated in numerous workshops and presentations and provided input to the vision. In particular, the team has been asked to support the web sensor portion of the vision.

The formation-flying team supported the ST-5 proposal development. The team provided input into the technologies and hardware necessary to support formation flying or constellation control among the nanosats. The proposal was accepted and the team anticipates the need to meet the challenge of the mission design, and incorporate formation-control technologies in a very tight budget and limited spacecraft capability.

Finally, the formation-flying team in cooperation with other NASA groups submitted their own proposal for the EO-3 OA. This proposal defined a formation-flying mission of up to 11 nanosats to do soil moisture and precipitation monitoring. Unfortunately, the proposal was rejected, but the team did gain valuable experience in the process and generated research that has been used to support other missions planning to use interferometry.

[Technical contact: John Bristow/572]

4.3 Advances in Navigation Technology

Increasing interest in maximizing autonomy, operations "beyond LEO," and distributed spacecraft has brought new challenges for navigation systems. Addressing and anticipating new requirements has led to technology initiatives in onboard navigation systems (ONS) using communications links, GPS orbit determination, and autonomous navigation for high-Earth, libration, gravity-assist, and deep-space orbits. The continuing needs of flight projects and future mission studies for navigation consulting have also been supported.

Recognizing the benefits of technology commercialization, in-house ONS and GPS technology has been transferred to Motorola and Orbital Sciences Corporation, and a provisional patent has been filed for a new type of GPS attitude determination sensor[1]. A web site[2] has been launched, currently focusing on GPS and ONS, that is intended to raise awareness among the GNCC community of navigation activities at GSFC, and stimulate further commercial utilization of NASA-developed technologies. Helping to ensure continued support of in-house development, funding from the Explorers and Cross-Enterprise Technology Development programs have been secured for GPS and ONS initiatives in the areas of formation flying, and highly elliptical and geostationary orbit applications of GPS.

4.3.1 Onboard Navigation Systems Using Communications Links

The Enhanced ONS (EONS) flight software package, schematically illustrated in figure 4-1, has been delivered to Motorola for integration with a navigation processor board. Motorola is currently developing the flight software interfaces and looking at board improvements for improving Doppler data accuracy and frequency independence. A mathematical specification for EONS that describes the algorithms associated with the integration of ONS capabilities with a spacecraft's ground systems communications receiver has been delivered, and a draft System Description and User's Guide (SD&UG) has been prepared.

[1] Compound Eye GPS Attitude & Navigation Sensor (CEGANS), patent number GSC 13966-1.

[2] http://geons.gsfc.nasa.gov

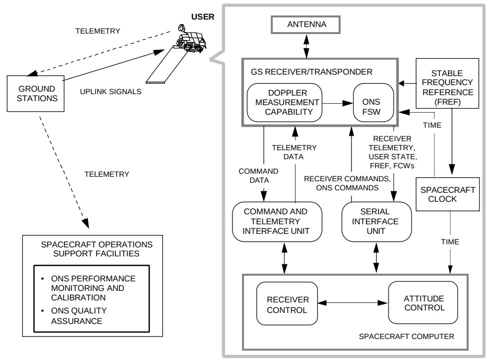

Figure 4-1

[Technical contact: Cheryl Gramling/572]

4.3.2 Global Positioning System (GPS) Orbit Determination

Studies supporting formation flying and highly elliptical and geosynchronous orbit missions have been accomplished. A major new release of the GPS Enhanced Orbit Determination (GEODE) flight software has been delivered. These accomplishments are described below. In addition, a paper describing relationships among semi-major axis, position, and velocity which are often not maintained in space applications of GPS was presented to the American Astronautical Society[3]. Figure 4-2 illustrates these results.

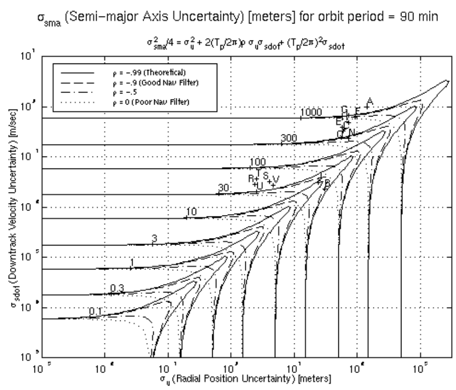

Figure 4-2

GPS State Vector Differencing. The accuracy of relative navigation solutions that can be achieved by differencing independently computed absolute state vectors, for a formation of eccentric, medium-altitude Earth-orbiting satellites using GPS measurements has been assessed. This scenario is shown in figure 4-3. Assessments show that relative state accuracy is five to six times worse when the differences are performed on deterministic point solutions rather than filtered solutions, and degrades rapidly as the number of measurements from uncommon GPS satellite vehicles (SV's) that are used in the solutions increases. The best accuracy (2 meters, 0.001 meter per second, root-mean-square (rms), and 10 meters, 0.005 meter per second, maximum) is achieved when four or more GPS SV's are mutually visible, and if the point solutions are computed using only measurements from GPS SV's common to both user satellites.

[3] Carpenter, J. Russell and Emil Schiesser, "The Importance of Semi-major Axis Knowledge in the Determination of Near-Circular Orbits," *Space Flight Mechanics 1999*, Univelt Publishing, San Diego.

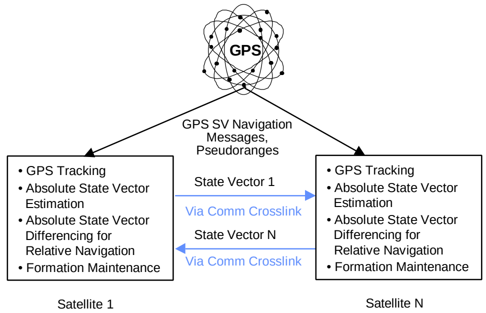

Figure 4-3

GPS in Highly Elliptical Orbits. The accuracy of navigation solutions computed for an eccentric medium-altitude Earth orbit (MEO) satellite as a function of GPS SV visibility has been investigated in a cooperative study with the University of Colorado at Boulder. The orbit studied is a geosynchronous transfer orbit, which has an apogee altitude that is well above the altitude of the GPS constellation. The analysis reported indicates that, with the increased visibility provided if lower strength signals from the GPS SV antenna side lobes can be acquired, navigation accuracy for a geosynchronous transfer orbit improves significantly, as shown in Figure 4-4. The rms total position errors reduce from 100 meters to 40 meters and the peak errors near apogee reduce from 250 meters to 100 meters. These results were reported to the Institute of Navigation's Annual Meeting[4].

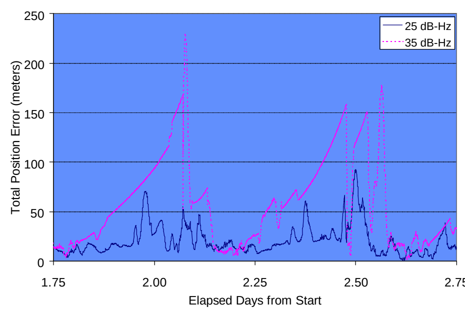

Figure 4-4

GEODE. GEODE provides the capability to use the GPS Standard Positioning System (SPS) to provide high-accuracy orbit determination and time autonomously onboard NASA spacecraft. For flight applications, the GEODE flight software can be integrated either within a GPS receiver or hosted on the spacecraft's onboard computer (OBC). For ground-processing applications, the GEODE flight software can be executed using GEODE ground-processing software. The current version includes revisions to incorporate algorithm enhancements that have been implemented in GEODE versions 4.01, 4.02, and 4.03. These enhancements include the following capabilities: estimation of both a correction to the atmospheric drag coefficient and the solar radiation pressure coefficient, extension of the gravity process noise model to handle eccentric and geostationary orbits, reformulation of the receiver clock bias model, and processing of measurements from all GPS space vehicles in view. Mathematical specifications and SD&UG documents reflecting these enhancements have been delivered.

[Technical contacts: Russell Carpenter/572; Jim Garrison/572]

4.3.3 "Compound Eye" GPS Attitude & Navigation Se nsor (CEGANS)

A novel GPS is under development which would provide data for both navigation and attitude. The sensor would be equipped with multiple directional antennas mounted on the convex hemispherical surface. Each antenna would be aimed to receive GPS signals from a restricted, but known visualization cone. By noting which GPS satellites are visible in the field-of-view of each antenna in the hemispherical array, the attitude of the sensor (and therefore the body to which it is attached) can be estimated to within 3 degrees without

[4] Moreau, M., et al. "GPS Receiver Architecture and Expected Performance for Autonomous GPS Navigation in Highly Eccentric Orbits," *Proceedings of the Annual Meeting of the Institute of Navigation*, June 1999.

resorting to the use of carrier-phase measurements. It is believed that optimization and signal-to-noise techniques can be applied to refine raw attitude estimates from this compact sensor to the subdegree range.

A paper was presented on this invention at the AIAA Boston conference last year[5] and was elected best paper of the session. The CEGANS was featured in a NASA Tech Briefs article in December 1998, and a provisional patent has since been issued by the patent office while a formal patent application awaits submission.

[Technical contact: David Quinn/572]

4.3.4 Autonomous Navigation for High-Earth, Libration, Gravity-assist, and Deep-space Orbits

An effort has been initiated to characterize the accuracy of autonomous navigation systems for satellites in regimes in which use of the GPS or Tracking and Data Relay Satellite System (TDRSS) is not feasible. This work assesses the feasibility of using standard spacecraft attitude sensors and communication components to provide autonomous navigation for high-Earth orbit (HEO) and libration-point orbit (LPO) missions, as illustrated in figure 4-5. Performance results are presented as a function of sensor measurement accuracy, measurement types, measurement frequency, initial state errors, and dynamic modeling errors. This analysis indicates that real-time autonomous navigation accuracies ranging from 100 meters rms for a 3-by-20-Earth-radii HEO satellite to 10 kilometers rms for an LPO satellite are achievable using high-accuracy attitude sensor and one-way Doppler measurements. This work was presented to the American Astronautical Society's Astrodynamics Specialists Conference[6].

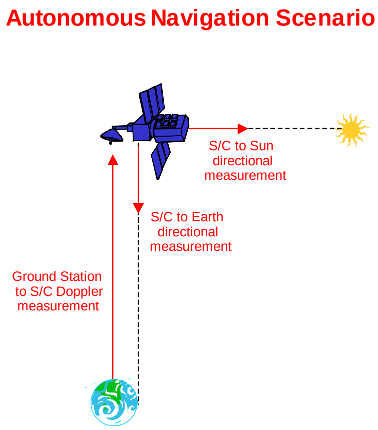

Figure 4-5

[Technical contacts: David Folta/571; Cheryl Gramling/572]

4.3.5 Navigation Studies Supporting Flight Projects and Future Missions

Flight projects and future missions supported included ICESAT, various magnetospheric survey missions, and the International Space Station version of the Honeywell Space Integrated GPS/INS (SIGI).

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[5] Crassidis, J.L, & Quinn, D.A., et al. "A Novel Sensor for Attitude Determination Using Global Positioning System Signals," *Proceedings of the American Institute of Aeronautics and Astronautics*, September 1998.

[6] Gramling, C., et al. "Autonomous Navigation Using Celestial Objects," AIAA Astrodynamics Specialists Conference, August 1999.

ICESAT. Expected orbit determination accuracies were estimated for candidate orbit determination scenarios with Selective Availability (SA) on and off. Raw geometric point solutions clearly will not provide the desired accuracy levels. Smoothing of point or filtered solutions significantly improves radial position and in-track velocity accuracy. If SA is on (current GPS operational configuration), the smoothed solution and post-processed differential solution can provide *radial* position accuracies of <10 meters and *in-track* velocity accuracies of <1 centimeter per second after 24 hours. Of these two methods, the smoothed solution method is considerably simpler to implement. If SA is off (expected GPS operational configuration in the 2000–2002+ timeframe), the filtered, smoothed, and post-processed differential solutions can provide *radial* position accuracies of <5 meters and *in-track* velocity accuracies of <1 centimeter per second after 24 hours. Of these three methods, the filtered and smoothed solution methods are considerably simpler to implement than the post-processed differential approach.

Magnetospheric Survey Missions. Orbit determination error analysis has been performed to determine the predicted accuracy for three magnetosphere-mapping missions: a mission that would use a constellation of 250 small satellites ("Magneto"), and two phases of a mission that uses a four-satellite formation (Magnetic Multiscale mission, MMS).

For the Magneto mission, each satellite would have a perigee height of 1.4 Earth radii. The apogee height values would range from 5 to 25 Earth radii. The inclination varies from 0 to 15 degrees. Tracking data consists of one-way return Doppler data from 11-meter S-band ground stations at Hawaii, Puerto Rico, Hartebeesthok, Diego Garcia, and the three DSN sites at Canberra, Goldstone, and Madrid; tracking station angle data could also be utilized. The analysis shows that 14-day tracking arcs with Doppler-only data will meet the mission's 3000 km position requirement.

MMS Phase I will require knowledge of absolute position and inter-spacecraft range to 100 km in its 1.2 by 12 Earth radii, 10 degree inclination orbit. Tracking data consisting of 30 minutes per orbit of Doppler data using Universal Space Network (USN) X-band ground stations located at Hawaii, Wallops Island, and Poker Flats, and both coherent and noncoherent Doppler data could be utilized. When using coherent Doppler data, an 8-day tracking span length should be used with at least one pass near perigee each day. When using noncoherent Doppler data, the frequency bias and drift should be estimated using an 8-day tracking span length with at least one pass near perigee each day. With respect to the inter-range accuracy, it has been determined that maximum error between two spacecraft was 60 meters when using a minimum tracking station elevation angle of 15 degrees, and 127 meters when using a minimum tracking station elevation angle of 7 degrees. It should be mentioned that the latter results correspond to a 97% to 99% correlation between the nonrandom errors common to the satellites, which is somewhat higher than the 90% to 95% correlation typically expected.

MMS Phase III differs from Phase I in having an 8x80 Earth radii orbit, and 28.5 degree inclination. Both DSN and USN tracking stations could be utilized. Due to the long period of this orbit (approximately 17 days), an 18-day tracking span has been studied. Results show that the DSN-only cases will not meet the 100 km requirement. The cases with the additional USN tracking will meet the 100 km requirement. The definitive accuracies using the DSN and USN tracking vary from 2 to 31 km. At least two perigee passes per data span are recommended.

SIGI. The SIGI provides an attitude determination capability that has been developed in-house. Support to this effort has included ground support equipment and performance analysis software development, consultation for and development of flight software, troubleshooting support to resolve coordinate systems and interface issues with both the GPS Test Facility's GPS signal simulator and the ISS flight software, and attitude performance analysis. Support has been provided for SIGI flight software releases 4.11 through 4.23. Consultation in the areas of attitude performance evaluation, SIGI software issues, and mission design has also been provided to JSC in support of a space shuttle flight test of the SIGI to occur on STS-101.

[Technical contact: Russell Carpenter*/572]*

4.4 Attitude Determination

4.4.1 Advanced Attitude Analysis

Additional studies were conducted on a Kalman Filter designed to estimate attitude and rate using quaternions from a quaternion output star tracker. The results of this testing indicate that this Kalman Filter is capable of providing highly accurate rate estimates eliminating the need for an expensive gyro. This algorithm was applied to flight data from the Rossi X-Ray Timing Explorer (RXTE). The flight star tracker data was converted to single frame attitude quaternions using the Q-method. The results were compared to the onboard attitudes computed from an EKF with star tracker data and a high performance gyro package. Figure 4-6 demonstrates the rate estimation capabilities during an RXTE maneuver. The rss of the error for this particular span of flight data was 6.1839e-4 degrees/second.

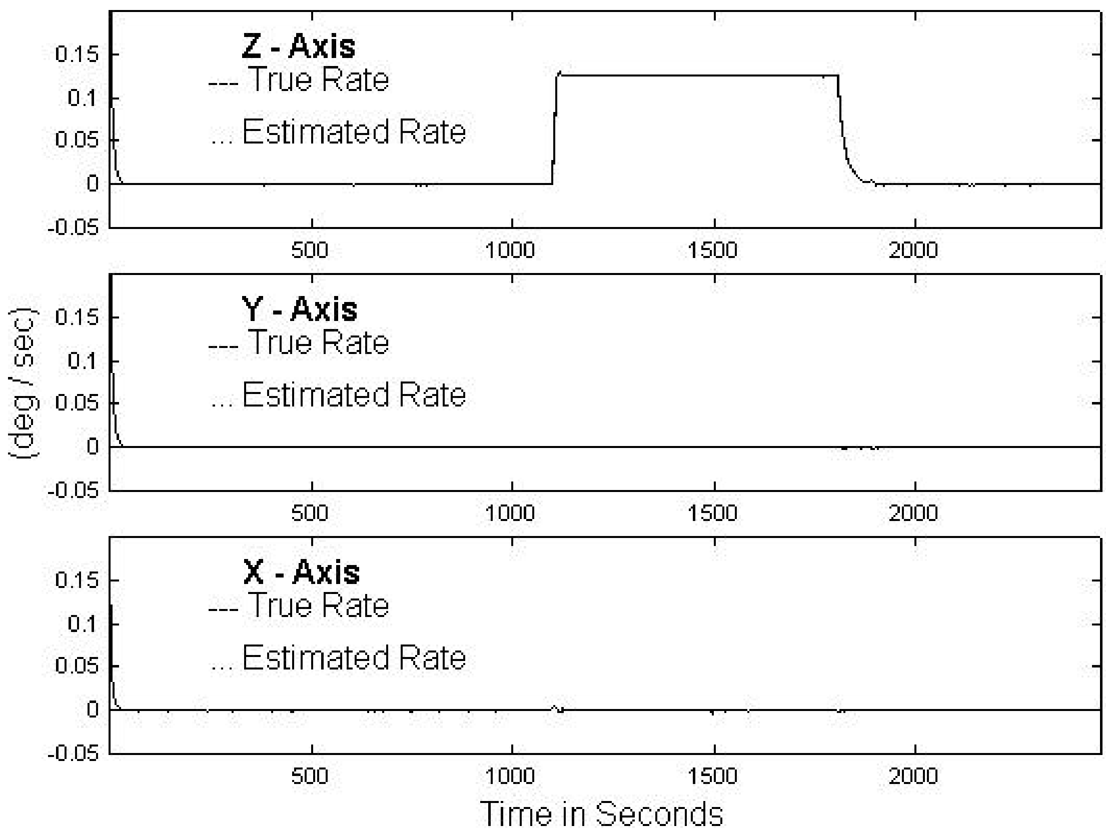

Figure 4-6 RXTE True Rate Versus Rate Estimate

An improved magnetometer calibration algorithm was developed and tested on flight data from the RXTE mission which had particularly difficult magnetometers to calibrate. Besides improved accuracy, this algorithm is more efficient and provides a covariance of the resultant calibration. Figure 4-7 provides a sampling of the magnetometer calibration for RXTE.

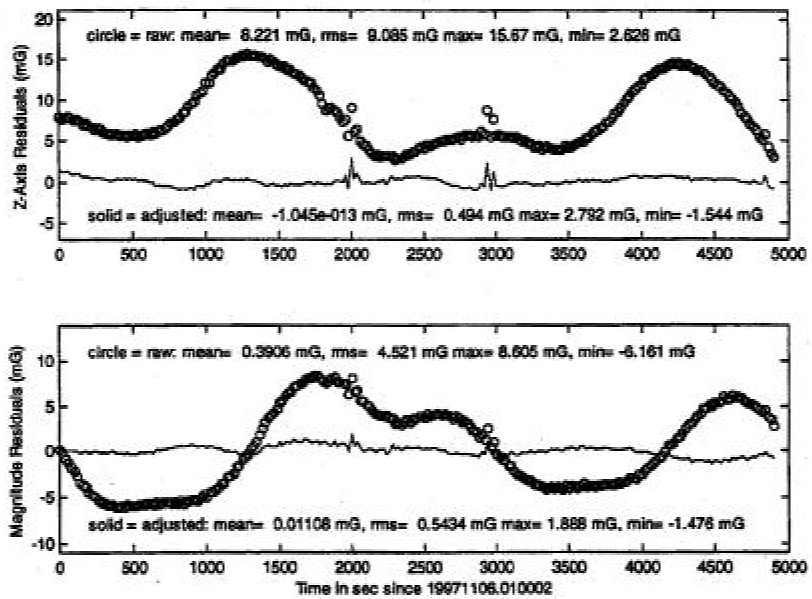

Figure 4-7 Magnetometer Calibration Using RXTE Flight Data (Solid Line is Post-Calibration Results)

[Technical contact: Rick Harman/572]

4.4.2 Attitude Models Task

The SKY2000 task has provided support in the form of new star catalogs (MARGIE–Minute of Arc Resolution Gamma ray Imaging Experiment–balloon mission/La. Tech), updated star catalogs (Landsat-7 & SWAS), consultation with mission personnel (Landsat-4/5, EOS AM/PM, UARS, SOHO, HST, GRO, WIRE), and for other groups in the space science field (STScI, Toshiba, CDS, TRW).

Version 2 of the SKY2000 Master Catalog (MC) was completed in September 1998 and represents a substantial improvement over Version 1 and a unique consolidation of astrometric data from the highest quality sources available. Position and proper motion data were improved by at least one order of magnitude and Johnson V&B magnitudes are now available for almost all of the ~300,000 stars in the MC. More than 4000 stars observed by the Ball CT-601 star trackers on the RXTE spacecraft now have observed CCD ST magnitudes in Version 2. IAU designations based on J2000.0 positions have been added to the catalog, while all previous identifiers (SKY2000, HD, SAO, DM, HR, WDS, PPM, AG, bright- and variable-star designations) have been retained. The IAU-approved identifiers allow new objects to be inserted without disrupting the natural order of the principal catalog identifier.

The SKY2000 MC Version 2 is available for download from the Flight Dynamics Division (FDD) web site and is in use by both the space hardware and the astronomy communities. Analysis conducted on the observational data from the Ball CT-601 star tracker on RXTE has resulted in a substantial improvement in the accuracy of the instrumental magnitude (Mi) prediction algorithm. That improvement, coupled with the actual observed CT-601 magnitudes now present in the MC, will provide end users significantly better Mi data for both onboard and ground-based attitude determination star catalogs.

[Technical contact: David Tracewell/572]

4.4.3 Magnetometer Navigation

GNCC personnel, jointly with Dr. Itzhack Bar-Itzhack of the Technion Israel Institute of Technology, have developed and tested a low-cost system for simultaneous and autonomous attitude, orbit, and rate estimation of a low-Earth orbit satellite. The system relies mainly on magnetometer data, a reliable and low-cost sensor. The estimation is performed using an Extended Kalman filter (EKF) algorithm. The filter state can be chosen to estimate all three components, namely attitude, orbit, and rate or a subset. This algorithm was successfully implemented for the Transition Region and Coronal Explorer (TRACE) mission. The TRACE sensor complement consisted of a magnetometer and a course (DSS). The results of estimating all 13 states can be seen in figures 4-8/-9/-10. During FY99, analysis of the attitude and orbit estimation subset was conducted to determine the feasibility of further improving the measurement data through the incorporation of more sophisticated sensor noise models. Dr. Wallace Larrimore of Adaptics, Inc. developed a statistical model of the RXTE magnetometer data. This model was incorporated into the RXTE EKF, resulting in improved attitude and orbit estimates. The results were presented at the 21st Annual AAS Guidance and Control Conference in a paper titled "Improved Modeling in a Matlab-Based Navigation System."

Negotiations with the CRV X-38 project at JSC began in FY99. The X-38 project is interested in determining if the magnetometer can provide a backup attitude solution to the prime attitude system based on GPS data. Attitude analysis using the magnetometer-based EKF will be conducted in Code 572. Numerous studies with the EKF will be conducted to determine the convergence potential from an unknown initial attitude within the time constraints of the necessary CRV orbit maneuvers. A preliminary result is given in figure 4-11. With simulated data, the EKF overcame an initial attitude error of 115 degrees and converged to within 5 degrees in 5 minutes, meeting the CRV constraints. Concurrently with the analysis, Code 573 will build the flight and test magnetometers for JSC based on the SMEX-lite magnetometer design. Following the test flight of the X-38 vehicle, the recorded magnetometer flight data will be analyzed in Code 570 and the magnetometer-based attitude estimates will be provided to JSC for further evaluation.

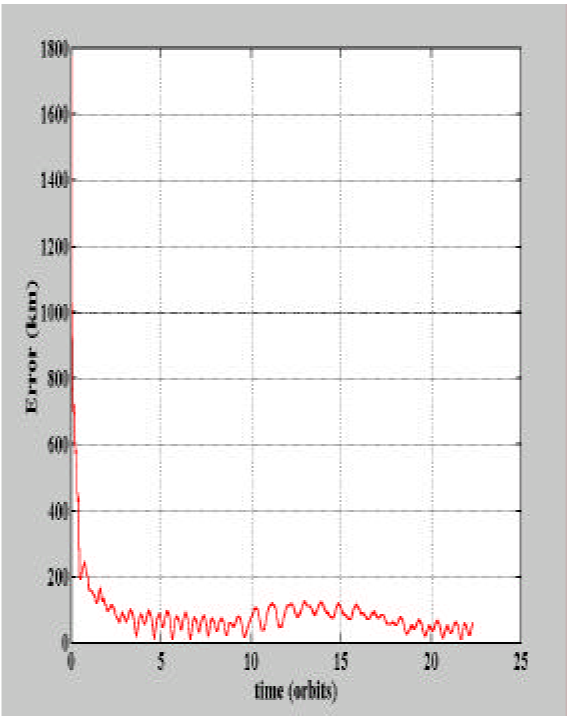

Figure 4-8 RSS of TRACE Orbital Position Error

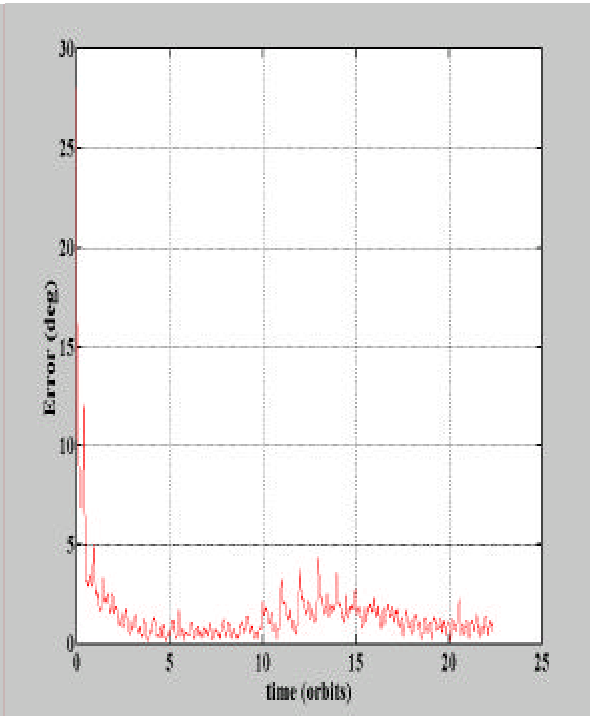

Figure 4-9 RSS of TRACE Attitude Estimation Errors

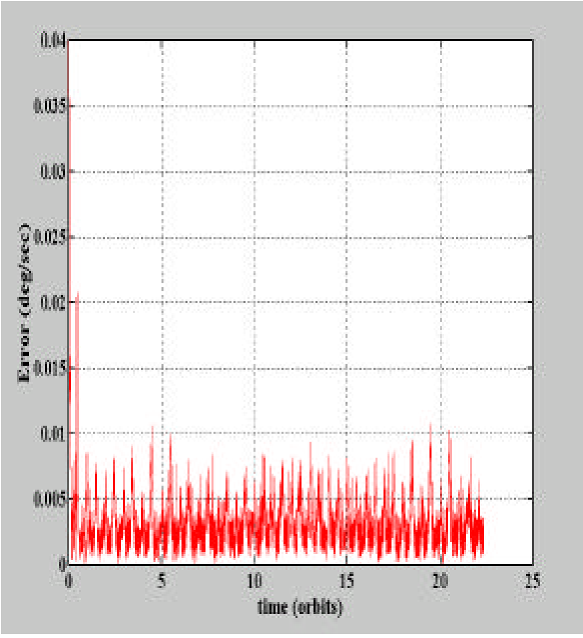

Figure 4-10 RSS of TRACE Rate Estimation Errors

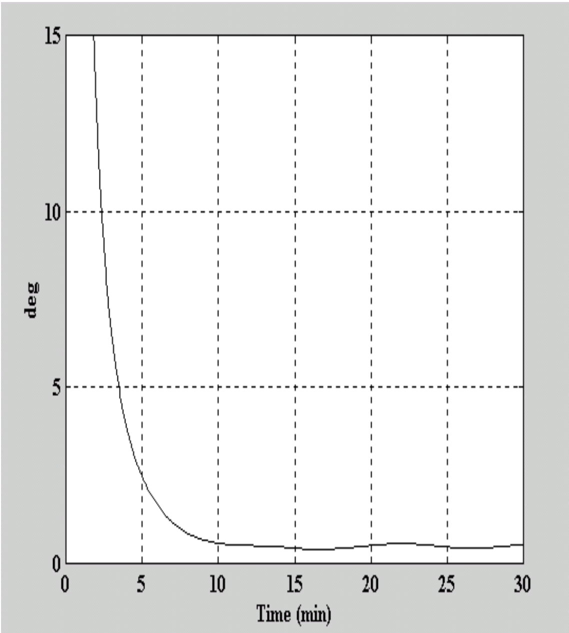

Figure 4-11 Preliminary CRV Magnetometer Attitude Test Result—Initial Error was 115 Degrees

[Technical contact: Julie Deutschmann/572]

5.0 GNCC Flight Dynamics Laboratory

GNCC began configuration of the Flight Dynamics Laboratory located in Building 11. This lab will be used for the development, test, integration, and operation of software systems to perform flight dynamics functions and analysis in support of space missions. When fully configured the lab will have the capability to receive spacecraft telemetry and navigation data, and have voice and video communication links for the performance of these functions.

Items completed were the room construction, installation of voice and video equipment, and installation of several computers. This initial configuration allowed support for the Lunar Prospector end of mission to be done from the lab.

Plans for the coming year call for the installation of computers, installation of an on line data storage device, and installation of servers. When this is complete the lab will be able to support all planned functions as well as provide an area for GNCC software analysis instruction.

[Technical contact: Sue Hoge/572]

6.0 Interagency Activities

6.1 CCSDS—Consultative Committee for Space Data Systems

Felipe Flores-Amaya (Code 572) represents GNCC as the chairman for the P1J Subpanel under the Consultative Committee for Space Data Systems (CCSDS).

The CCSDS is an international organization of space agencies interested in mutually developing standard data handling techniques to support space research conducted exclusively for peaceful purposes. Ref. http://www.ccsds.org/

Subpanel P1J is specifically chartered to investigate and recommend Navigation Data standards. P1J currently has 16 members, representing the following international agencies: Chinese Academy of Space Technology (CAST), China; Communications Research Centre (CRC), Canada; Centre National D'etudes Spatiales (CNES), France; Deutsche Zentrum fur Luft- und Raumfahrt (DLR), Germany; European Space Agency (ESA), Europe; National Aeronautics and Space Administration (NASA), USA; and National Space Development Agency (NASDA), Japan.

The work of P1J is accomplished primarily at workshops, conducted at least twice a year, at facilities coordinated by the hosting member agency. The main task of P1J is to generate documents defining the preferred standards for the exchange of navigation data. A draft of the latest document was reviewed during the most recent workshop, May 1999 at Newport Beach, California.

Future work will involve investigating
- Proximity and in situ navigation
- Interface with GPS, GLONASS, and similar systems
- Autonomous navigation
- Tracking stations on other planets
- GPS-like constellations around other planets

[Technical contact: Felipe Flores-Amaya/572]

6.2 Flight Mechanics Symposium

The FDAB conducted the Flight Mechanics Symposium, May 18–20, 1999. The purpose of this symposium was to provide a forum for specialists from industry, academia and Government agencies to present, discuss and exchange information on a wide variety of topics, including attitude determination, orbit determination, attitude control system analysis and design, sensor calibration, mission analysis, mission design, orbit control, and error analysis. A total of 40 papers were presented at the 1999 symposium. The papers presented at this symposium are available in a formal NASA publication (NASA/CP—1999–209235).

[Technical contact: John P. Lynch/572]

7.0 ISO9000

The FDAB complied with all requirements to ensure readiness for GSFC ISO9000 certification. For details about GSFC ISO activities, please refer to http://arioch.gsfc.nasa.gov/iso9000/index.htm

[Technical contact: Felipe Flores-Amaya/572]

8.0 Outreach Activities

8.1 University Satellite Operations—SAMPEX

The GNCC awarded a new 5-year contract to the University of Maryland for SAMPEX Flight Dynamics Operations support. SAMPEX, the first in the series of small explorer class satellites, was launched in 1992. Through a partnership with the GNCC, the University of Maryland developed the capability to perform some spacecraft operations. With this new contract, complete responsibility has been given to the university for performing operational orbit determination, orbit prediction, event scheduling (e.g., ground-station access times, shadow timing, ground track), attitude determination, and sensor monitoring for the SAMPEX mission. GNCC engineers still provide consultation support and program review. Through this relationship with the university, the GNCC also participated in classroom lectures as guest speakers and offered tours of GSFC facilities to university students.

[Technical contact: Thomas Stengle/572]

8.2 Graduate Student Researchers Program—GSRP

The Graduate Student Researchers Program (GSRP) offers graduate students summer employment positions through the University Programs Office. This is a competitive placement and is highly regarded. The student worked with GSFC's GNCC. As part of a 3-year plan, the student is matched with a designated staff member as mentor for about 10 weeks (June 1–August 8) at GSFC in Greenbelt, Maryland. In addition to offering a meaningful work experience, the program offers innovative ideas from outstanding students for mission and activities at GSFC. This year we had the pleasure of working with Mr. Jose Guzman, a Ph.D. candidate from Purdue University. Mr. Guzman worked on Dynamical System Theory Concepts in regard to manifolds for libration orbit transfers. He held a class and presented his work in manifolds to the mentor and other GNCC professionals. This work will be used for libration orbit design.

[Technical contact: David Folta/571]

8.3 Visiting Student Enrichment Program—VSEP

The Visiting Student Enrichment Program (VSEP) offers students summer employment positions with the Universities Space Research Association (USRA), working with GSFC's Earth & Space Data Computing Division and numerous Center organizations that may include the GNCC. A selected student is matched with a designated staff member as mentor for about 10 weeks (June 1–August 8) at GSFC in Greenbelt, Maryland. In addition to offering a meaningful work experience, the program offers field trips and lectures to provide broader appreciation for the mission and activities at GSFC. This year we had the pleasure of hosting Mr. Steven Hughes, a master's candidate from Virginia Tech University. Mr. Hughes worked on Formation Flying Concepts in regard to attitude control and spacecraft pointing. He gave a final presentation to the VSEP mentors and students.

[Technical contact: David Folta/571]

8.4 Public Education/Community Outreach

Supported the National Technical Association (NTA) annual conference, science fair & engineering judging events, rocket building/engineering design projects, speeches (open, award, closing & graduation ceremonies), program visits for GSFC mentor/student/fellow events, education/career conferences and panels, online interactive session, and television/radio/magazine interviews.

[Technical contact: Aprille Ericsson- Jackson/572]

Appendix A—Conferences and Papers

Bristow, J.O., G.T Dell, K.B Chapman, and D.L. Rosenberg, "Autonomous Formation Flying From the Ground to Flight," 1999 Flight Mechanics Symposium, GSFC, Greenbelt, MD.

Bristow, J.O., D. Weidow, "NASA/DoD University Nanosatellites for Distributed Spacecraft Control," 13th Annual Conference on Small Satellites, Logan, UT.

Carpenter, J.R., "Feasibility of Decentralized LQG Control of Autonomous Satellite Formations," 1999 Flight Mechanics Symposium, GSFC, Greenbelt, MD.

Carpenter, J.R., D.C. Folta, and D.A. Quinn, "Integration of Decentralized LQG Control into GSFC's Universal 3-D Formation-Flying Algorithm," 1999 AIAA GN&C Conference, Portland, OR.

Folta, D.C., and D.A. Quinn, "A Universal 3-D Method for Controlling the Relative Motion of Multiple Spacecraft in Any Orbit," AIAA/AAS Astrodynamics Specialist Conference, Boston, MA.

"Janus Trajectory Design," Greg Marr, presented at the Flight Mechanics Symposium at GSFC, sponsored by Code 572, May 1999.

Lauri Newman attended the AAS/AIAA Astrodynamics Specialist Conference in Girdwood, AK, on August 15–19, 1999.

McComas, David C., James R. O'Donnell, Jr., Ph.D., and Stephen F. Andrews, "Using Automatic Code Generation in the Attitude Control Flight Software Engineering Process," 1998 Software Engineering Laboratory Conference, GSFC, Greenbelt, MD, December 1998.

O'Donnell, James R., Jr., Ph.D., Stephen F. Andrews, and David C. McComas, "Development and Testing of Automatically Generated ACS Flight Software for the MAP Spacecraft," 14th International Symposium for Space Flight Dynamics, Iguassu Falls, Brazil, February 1999.

O'Donnell, James R., Jr., Ph.D., Stephen F. Andrews, Aprille J. Ericsson-Jackson, Ph.D., Thomas W. Flatley, Ph.D., David K. Ward, and P. Michael Bay, "Backup Attitude Control Algorithms for the MAP Spacecraft," 1999 Flight Mechanics Symposium, GSFC, May 1999.

"On-Orbit Performance of the TRMM Mission Mode," Brent Robertson, Sam Placanica, Wendy Morgenstern, Joseph Hashmall (CSC), Jonathan Glickman (CSC) and Gregory Natanson (CSC), 14th International Symposium on Space Flight Dynamics, February 1999.

"The Importance of Semi-major Axis Knowledge in the Determination of Near-Circular Orbits," Carpenter, J. Russell, and Emil Schiesser, *Space Flight Mechanics 1999*, Univelt Publishing, San Diego.

"TRMM On-Orbit Attitude Control System Performance," Brent Robertson, Sam Placanica and Wendy Morgenstern, 22nd Annual AAS Guidance and Control Conference, February 1999.

Ward, David K., Stephen F. Andrews, David C. McComas, and James R. O'Donnell, Jr., Ph.D., "Use of the MATRIXx Integrated Toolkit on the Microwave Anisotropy Probe Attitude Control System," 1999 AAS Guidance, Navigation and Control Conference, Breckenridge, Colorado, February 1999.

Appendix B—Acronyms and Abbreviations

The appendix gives the definitions of acronyms used in this document.

AAS	American Astronautical Society
ACE	Attitude Control Electronics
ACS	Attitude Control System
AFRL	Air Force Research Laboratory
AI	Artificial Intelligence
ARC	Ames Research Center
C&DH	Command & Data Handling
CAST	Chinese Academy of Space Technology
CCD	Charged Coupled Device
CCSDS	Consultative Committee for Space Data Systems
CDR	Critical Design Review
CMP	Central Mounting Plate
CNES	Centre National D'etudes Spatiales
COTS	Commercial Off-the-Shelf
CPU	Central Processing Unit
CPT	Comprehensive Performance Test
CRC	Communications Research Centre
CREAM	Cosmic Ray Energetics and Mass
DLR	Deutsche Zentrum fur Luft- und Raumfahrt
DLS	Double Lunar Swingby
DSN	Deep Space Network
DSS	Digital Sun Sensor
DST	Dynamical Systems Theory
ECCO	Extremely Heavy Galactic Cosmic-Ray Composition Observer
EIKF	Extended Interlaced Kalman Filter
EKF	Extended Kalman Filter
ELV	Expendable Launch Vehicle
EO-1	Earth Orbiter-1
EOS	Earth Observing System
ERBS	Earth Radiation Budget Satellite
ESA	European Space Agency
ESTO	Earth Science Technology Office
FAST	Fast Auroral Snapshot Explorer
FD	Flight Dynamics
FDAB	Flight Dynamics Analysis Branch
FDCL	Flight Dynamics & Control Laboratory
FDS	Flight Dynamics System
FDSS	Flight Dynamics Support System
FM	Flight Mechanics
FOT	Flight Operations Team
FOV	Field of View
FY	Fiscal Year
GADFLY	GPS Attitude Determination Flyer
GEAS	GPS Error Analysis System
GEM	Goddard Electronics Module
GEODE	GPS Enhanced Orbit Determination Experiment
GLONASS	Global Orbiting Navigation Satellite System
GN	Ground Network
GNCC	Guidance, Navigation and Control Center
GOES	Geostationary Operational Environmental Satellite
GOTS	Government-off-the-shelf
GPS	Global Positioning Satellite

GRO	Gamma Ray Observatory
GSFC	Goddard Space Flight Center
GSRP	Graduate Student Researchers Program
HGA/CPU	High-Gain Antenna/Contact Prediction Utility
HTML	HyperText Markup Language
I&T	Integration and Test
IKF	Interlaced Kalman Filter
IMAGE	Imager for Magnetopause-to-Aurora Global Exploration
IMDC	Integrated Mission Design Center
ISS	International Space Station
JHU/APL	Johns Hopkins University/Applied Physics Laboratory
LP	Lunar Prospector
MAP	Microwave Anistropy Probe
MARGIE	Minute of Arc Resolution Gamma ray Imaging Experiment
MAXIM	Micro-Arc-second X-ray Imaging Mission
MIT	Massachusetts Institute of Technology
MMS	Magnetic Multi-scale Mission
MOC	Mission Operations Center
MSRD	Mission Support Requirements Document
MTASS	Multimission Three-Axis-Stabilized Attitude Support System
NASA	National Aeronautics and Space Administration
NASDA	National Space Development Agency of Japan
NGST	Next Generation Space Telescope
NGXO	Next Generation X-Ray Observatory
NMP	New Millennium Program
NOAA	National Oceanic and Atmospheric Administration
OBC	Onboard Computer
PC	Personal Computer
PI	Principal Investigator
POES	Polar Orbiting Environmental Satellites
QUEST	Quaternion Estimation
RMS	Root-Mean-Square
RTADS	Real-Time Attitude Determination System
RWA	Reaction Wheel Assembly
RXTE	Rossi X-Ray Timing Explorer
SA	Selective Availability
SABER	Sounding of the Atmosphere Using Broadband Emission Radiometry
SAGE	Stratospheric Aerosol and Gas Experiment
SAIL	Satellite Artificial Intelligence Laboratory
SAMPEX	Solar, Anomalous, and Magnetospheric Particle Explorer
SAO	Solar Astronomical Observatory
SBIR	Small Business Innovation Research
SMEX	Small Explorer
SOHO	Solar and Heliospheric Observatory
SOMO	Space Operations Management Office
SPC	Spectroscopic and Polarimetric Coronagraph
SPECS	Submillimeter Probe and the Evolution of Cosmic Structure
SPS	Standard Positioning Service
STK	Satellite Tool Kit
SWAS	Submillimeter Wave Astronomy Satellite
TARA	Two Axis Rate Assembly
TDRS	Tracking Data Relay Satellite
TDRSS	Tracking Data Relay Satellite System
TRACE	Transition Region and Coronal Explorer
TRMM	Tropical Rainfall Measuring Mission
ULDB	Ultra Long Duration Balloon

URL	Uniform Resource Locator
VO	Visualization Option
VSEP	Visiting Student Enrichment Program
WIRE	Wide-Field Infrared Explorer
WWW	World Wide Web

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13. ABSTRACT *(Maximum 200 words)*

This report summarizes the major activities and accomplishments carried out by the Flight Dynamics Analysis Branch (FDAB), Code 572, in support of flight projects and technology development initiatives in Fiscal Year (FY) 1999. The report is intended to serve as a summary of the type of support carried out by the FDAB, as well as a concise reference of key analysis results and mission experience derived from the various mission support roles. The primary focus of the FDAB is to provide expertise in the discipline of flight dynamics, which involves spacecraft trajectory (orbit) and attitude analysis, as well as orbit and attitude determination and control. The FDAB currently provides support for missions involving NASA, government, university, and commercial space missions, at various stages in the mission life cycle.

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